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Preliminary Economic Analysis of a Lime Spray Dryer FGD System

(U.S.) Tennessee Valley Authority
Muscle Shoals, AL

Prepared for

Industrial Environmental Research Lab.
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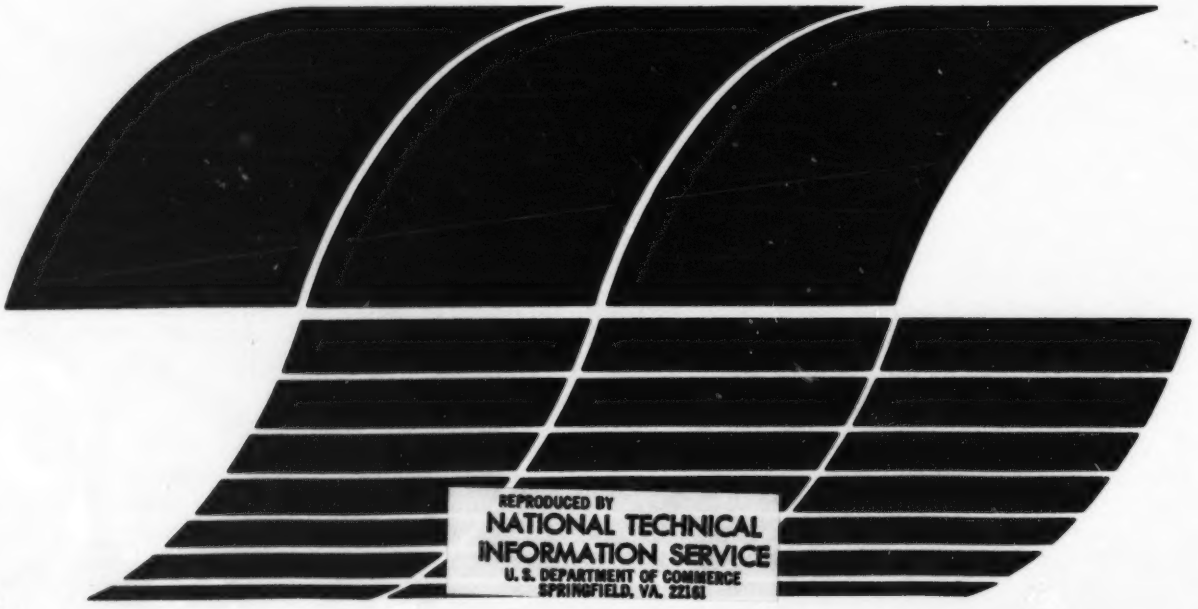
Interagency Energy/Environment R&D Program Report



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16. ABSTRACT The report gives results of a preliminary economic analysis of two flue gas desulfurization (FGD) processes (one dry and one wet) for a new 500-MW power plant burning Western coal having 0.7% sulfur, 9.7% ash, and a heating value of 9700 Btu/lb and meeting current new source performance standards (70% SO2 removal and 0.03 lb/MBtu particulate emission). The generic lime spray-dryer process used a baghouse for particulate collection, while the wet limestone slurry process had an electrostatic precipitator (ESP) for particulate control. (In addition to the coal noted, the final report will include an economic evaluation for both low- and high-sulfur Eastern coals.) The analysis shows capital investment costs of $132/kW for the lime process for SO2 and particulate removal, and $186/kW for the limestone process. First year and levelized annual revenue requirements are 6.20 and 8.55 mills/kW, respectively, for the lime process; and 8.55 and 11.71 mills/kW, respectively, for the limestone process. Sensitivity analyses indicate that: (1) delivered raw material costs do not significantly affect the annual revenue requirements for either process; (2) annual revenue requirements for the spray dryer are insensitive to the raw material stoichiometry; and (3) waste disposal for the wet process, even with fixation, is more expensive than for the dry process.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Calcium Carbonates	Pollution Control	13B	
Economic Analysis	Spray Drying	Stationary Sources	05C	13H
Analyzing	Coal		14B	21D
Desulfurization	Combustion		07A,07D	
Flue Gases			21B	
Calcium Oxides			07B	

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by

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Muscle Shoals, Alabama 35660

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ABSTRACT

A preliminary economic analysis of two flue gas desulfurization (FGD) processes, one dry and one wet, were performed for a new 500-MW power plant burning western coal having 0.7% sulfur, 9.7% ash, and a heating value of 9,700 Btu/lb and meeting current new source performance standards (70% SO_2 removal and 0.03 lb/MBtu particulate emission). The generic lime spray dryer process used a baghouse for particulate collection, while the wet limestone slurry process had an electrostatic precipitator (ESP) for particulate control. In addition to the coal noted, the final report will include an economic evaluation for both a low- and a high-sulfur eastern coal.

Results of the preliminary analysis show that the capital investment costs for the generic lime spray dryer process for SO_2 and particulate removal are $132/kW while being $186/kW for the ESP-wet limestone slurry combination. First-year and levelized annual revenue requirements are 6.20 and 8.55 mills/kW, respectively, for the dry FGD process; 8.55 and 11.71 mills/kWh, respectively, for the wet process.

Sensitivity analyses indicate (1) delivered raw material costs do not significantly affect the annual revenue requirements for either the wet or dry process, (2) annual revenue requirements for the spray dryer are insensitive to the raw material stoichiometry, and (3) waste disposal for the wet process even with fixation is still more expensive than for the generic lime spray dryer process.

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ABBREVIATIONS AND CONVERSION FACTORS

ABBREVIATIONS

aft^3	actual cubic feet	kg	kilogram
Btu	British thermal unit	kℓ	kiloliter
^oC	degrees Celsius	kW	kilowatt
dia	diameter	kWh	kilowatthour
ESP	electrostatic precipitator	lb	pound
^oF	degrees Fahrenheit	k	thousand (kilo)
FD	forced draft	M	million (mega)
FGD	flue gas desulfurization	min	minute
ft	feet	mol	mole
ft/sec	feet per second	MW	megawatt (electrical)
g	gram	ppm	parts per million (volume)
gal	gallon	sft^3	standard cubic feet
gpm	gallons per minute	sec	second
gr	grain	vol	volume
hr	hour	wt	weight
ID	induced draft	yr	year
in.	inch		

CONVERSION FACTORS

To convert from English units	To metric units	Multiply by
acres	hectares	0.405
British thermal units	kilocalories	0.252
degrees Fahrenheit minus 32	degrees Celsius	0.5556
feet	centimeters	30.48
square feet	square meters	0.0929
cubic feet	cubic meters	0.02832
cubic feet per minute	cubic meters per second	0.000472
gallons (U.S.)	liters	3.785
gallons per minute	liters per second	0.06308
grains per cubic foot	grams per cubic meter	2.288
horsepower	kilowatts	0.746
inches	centimeters	2.54
pounds (mass)	kilograms	0.4536
pounds per cubic foot	kilograms per cubic meter	16.02
pounds (force) per square inch	Pascals (Newton per square meter)	6895
miles	meters	1609
standard cubic feet per minute (60^oF)	normal cubic meters per hour (0^oC)	1.6077
tons (short)[a]	metric tons	0.9072

a. All tons, including tons of sulfur, are expressed in short tons.

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PRELIMINARY ECONOMIC ANALYSIS OF A LIME SPRAY DRYER FGD SYSTEM

EXECUTIVE SUMMARY

Dry-scrubbing flue gas desulfurization (FGD) technology using a concentrated solution or suspension of a reactive absorbent in a spray dryer is a recent development in electric utility FGD. It is receiving extensive attention, at the present time, and contracts have been awarded for nine commercial installations. Much of this interest is due to some potentially significant technical advantages over conventional wet FGD technology--the process design is relatively simple; stack gas reheat may be substantially reduced or eliminated, and the product is a dry waste rather than a wet sludge.

These dry scrubbers have one significant disadvantage--the use of an expensive (relative to limestone) alkali absorbent, either lime or soda ash. The raw material cost penalty for using lime or soda ash must be offset by savings in capital charges and maintenance costs for spray dryer systems to be economically competitive with the wet limestone systems. Minimizing these raw material costs is one of the reasons that the first commercial utility applications of these systems are on boilers fired with lignite and subbituminous coals. Both of these types of coals are normally low in sulfur and, therefore, the amount of expensive alkali raw material to be consumed in the FGD system is minimized. (In fact, the average fuel sulfur level at the utility boilers currently under contract is less than 1.0%.) These fuels also produce a highly alkaline ash which, if recycled through the spray dryer, can further reduce makeup raw material requirements.

Although capital investments and revenue requirements for these processes have been estimated by various process vendors and compared with a conventional wet limestone slurry process, no independent economic comparisons based on comparable design and economic premises have been published. The purpose of this economic evaluation is to compare the costs of the spray dryer FGD technology with those of the limestone slurry process based on the technical and economic premises developed jointly by the Environmental Protection Agency (EPA) and the Tennessee Valley Authority (TVA).

In addition to the base-case evaluations, sensitivity analyses of raw material costs and stoichiometries on the annual revenue requirements were performed. The capital investment and annual revenue requirements

for the limestone slurry process with sludge fixation by the IU Conversion Systems, Incorporated (IUCS) process and landfill disposal were determined for comparison with the costs of pond disposal.

DESIGN AND ECONOMIC PREMISES

Design Premises

Table S-1 lists the major design premises for this study. The base-case power plant is a new, 500-MW coal-fired power unit located in the Great Plains - Rocky Mountain region. The fuel is a subbituminous coal with a heating value of 9,700 Btu/lb and containing 0.7% sulfur (dry basis), 9.7% ash, and 16% moisture. The boiler heat rate is 9,500 Btu/kWh.

TABLE S-1. MAJOR DESIGN PREMISES

Item	Premise
Power plant	New, Great Plains - Rocky Mountain region, 500-MW coal-fired boiler, 9,500 Btu/kWh heat rate
Operating schedule	130,400 hr, 30-yr life, 5,500-hr first-year operation
Fuel	Subbituminous coal; 9,700 Btu/lb, 0.7% sulfur, 9.7% ash, 16% moisture
Base year	Capital investment: mid-1982 Revenue requirements: 1984
FGD waste disposal	Limestone: clay-lined pond Generic lime spray dryer: landfill
SO_2 removal efficiency	70%
Particulate removal efficiency	99.8% (0.03 lb of particulates/MBtu heat input)
SO_2 absorber redundancy	33% (3 operating trains, 1 spare)

The FGD unit includes all the equipment necessary to meet the recent (June 1979) new source performance standards (NSPS) for both particulate matter (0.03 lb/MBtu heat input) and SO_2 (overall 70% removal for low-sulfur coals). The overall design for the generic lime spray dryer system is based on vendor information, while the design of the limestone slurry process is based on in-house data and previous evaluations by TVA.

Economic Premises

The project is assumed to begin in mid-1980 with a 3-yr construction period ending in mid-1983. The midpoint of construction costs, and therefore the basis for the capital investment costs, is mid-1982. The revenue requirements are based on 1984 costs. Delivered costs for raw materials are projected based on mid-1979 prices in the Great Plains - Rocky Mountain region. Labor rates for 1984 for this region are assumed to be equivalent to those for a midwestern location and are projected from current midwestern labor costs.

Capital investment estimate is made up of direct investment, indirect investment, and other capital charges. The direct investment is based on equipment lists and other installation costs (such as piping, electrical, instrumentation, etc.) are factored from the equipment costs. Indirect investment (engineering design and supervision, construction expense, etc.) is estimated based on the direct investment. Other capital costs (allowance for startup and modification, interest during construction, etc.) are estimated from the total direct and indirect investment. These preliminary capital investment estimates are normally considered to have a -20% to +40% range of accuracy (i.e., in an actual application of the generic lime spray dryer process for this 500-MW boiler the capital investment could range from 20% less to 40% more than the projected $132.3/kW).

Two types of annual revenue requirements are projected--first year and levelized. Both are based on 5,500 hours of operation per year at full load (about a 63% capacity factor) and both use a levelized capital charge. Levelized annual revenue requirements differ from first-year annual revenue requirements in that they take into consideration the time value of money over the life of the FGD unit and are calculated using a 10% discount factor, 6% inflation factor, and a 30-yr economic life.

PROCESS BACKGROUND AND DESCRIPTION

Generic Lime Spray Dryer Process

The generic lime spray dryer process (Figure S-1) contains only two major equipment items, a spray dryer and a baghouse. Most of the flue gas from the boiler passes untreated to the spray dryer where it contacts an atomized slurry of lime and recycled waste. The sulfur oxides are absorbed and react with the lime, and fly ash alkali if present, to form calcium sulfite and calcium sulfate. The slurry concentration is adjusted so that the water injected into the spray dryer is insufficient to saturate the flue gas and the resulting waste material leaves as dry particulate matter entrained in the flue gas.

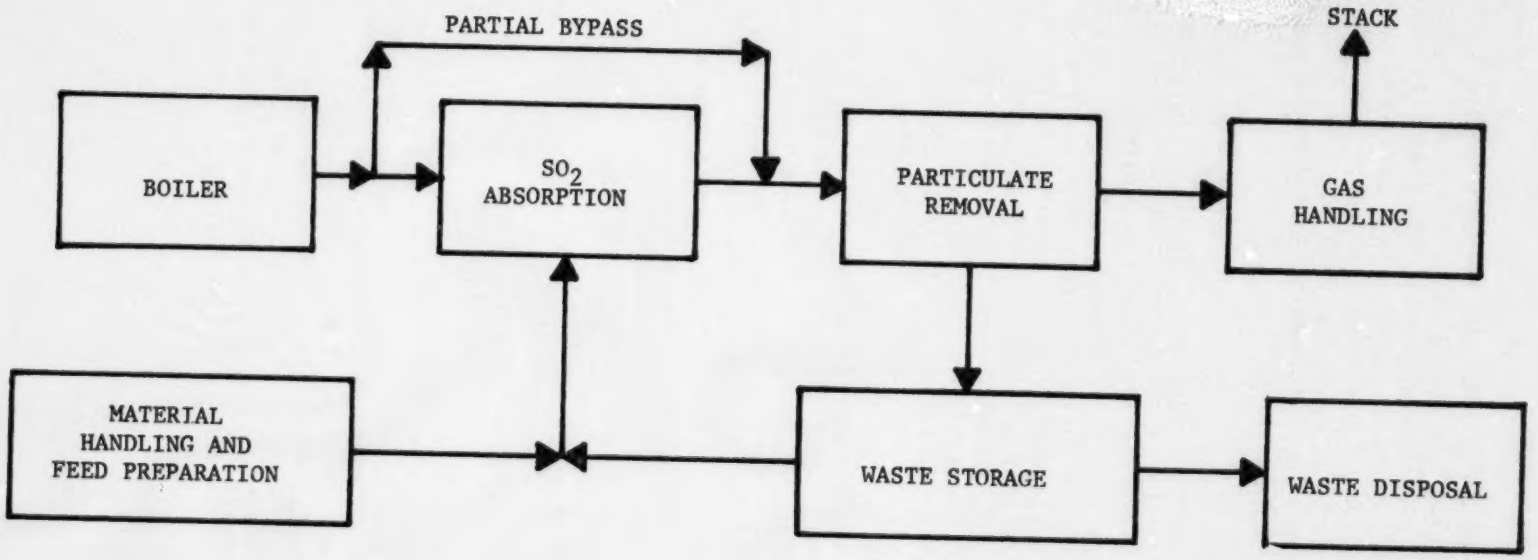

Figure S-1. Generic lime spray dryer process. Block flow diagram.

The remaining flue gas from the boiler (22% of the total gas rate) bypasses the spray dryers and enters the flue gas ducts downstream of the spray dryers but before entering the baghouse. The system is designed such that the overall SO_2 removal will meet the recently promulgated (June 1979) NSPS (i.e., 70% removal for coal containing 0.7% sulfur).

The calcium-based particulate matter formed in the spray dryer and the fly ash from the boiler are removed in the baghouse, which is designed to meet the NSPS for particulate matter (0.03 lb/MBtu). Part of the waste material from the baghouse (both fly ash and calcium-based salts) is temporarily stored in a hopper before trucking to the landfill. The remainder is reslurried and recycled to the spray dryer.

The only other area is the lime preparation area where lime is stored, slaked, and pumped to the spray dryers. Surge capacity for both the dry lime and the lime slurry is included.

Limestone Slurry Process

The limestone slurry process (Figure S-2) is also a relatively simple process containing only two major equipment items, a high-efficiency electrostatic precipitator (ESP) and a venturi/spray tower wet scrubber. Although ESP's are not normally considered a part of the limestone slurry process, they have been included in this limestone slurry process so that it can be compared with the generic lime spray dryer process.

Flue gas from the boiler passes through the ESP for fly ash removal to meet the NSPS. (The fly ash from the ESP is trucked to the disposal pond.) The flue gas from the ESP is divided into two streams. Most (72%) of the flue gas enters the SO_2 scrubbers where 90% of the entering SO_2 is absorbed to achieve the overall 70% SO_2 removal required by the NSPS for the 0.7% sulfur coal. The remaining flue gas bypasses the scrubbers and enters the flue gas ducts after the scrubber, providing sufficient heat to make reheating unnecessary.

Part of the recirculating slurry in the absorption section is bled off and pumped to the disposal pond. The wet calcium sulfite-sulfate salts settle out as a 40% (by weight) sludge, and the supernate is recycled for reuse in the process.

The major remaining processing area is the limestone preparation area where the makeup limestone is stored, crushed, milled, and slurried before being added to the recirculating slurry. Surge capacity for both dry limestone and the limestone slurry is included.

ECONOMIC EVALUATION AND COMPARISON

Preliminary estimates of capital investment, first-year revenue requirements, and levelized annual revenue requirements were prepared for both the generic lime spray dryer process and the limestone slurry process based on the design and economic premises. These results are shown in Table S-2.

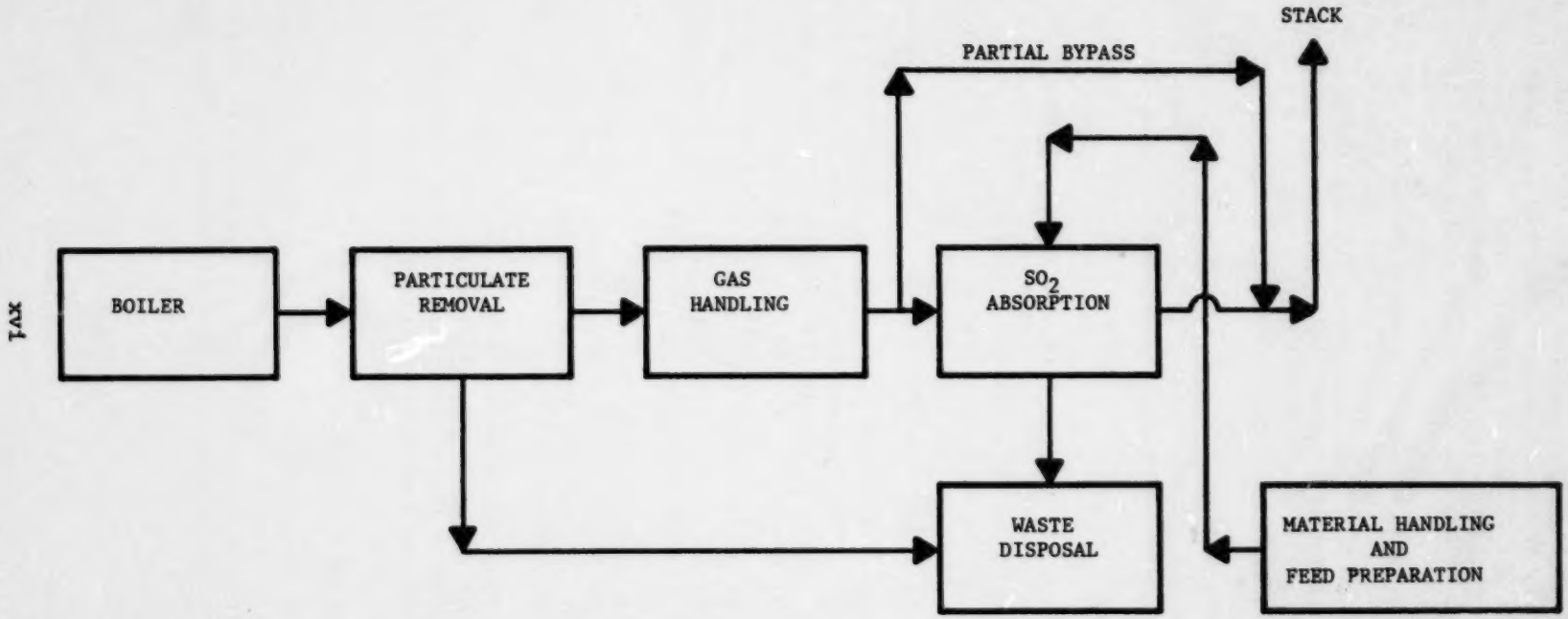

Figure S-2. Limestone slurry process. Block flow diagram.

TABLE S-2. BASE-CASE COMPARISON OF CAPITAL INVESTMENTS AND ANNUAL REVENUE REQUIREMENTS

	Generic lime spray dryer process	Limestone slurry process
Capital investment (1982 $)		
M$	66.2	93.2
$/kW	132.3	186.4
Total first-year revenue requirements (1984 $)		
M$	17.04	23.50
mills/kWh	6.20	8.55
Levelized annual revenue requirements (1984 $)		
M$	23.52	32.19
mills/kWh	8.55	11.71

The capital investment for the generic lime spray dryer process is $66.2M ($132.3/kW) in mid-1982 dollars. The total direct investment portion of the capital investment, which includes equipment costs and installation expenses, accounts for $32.5M. The major processing areas, in terms of investment required, are particulate matter removal ($11.1M), gas handling ($7.2M), and SO_2 absorption ($7.2M). These areas alone account for 78% of the direct investment. The indirect investments (engineering design and supervision, architect and engineering contractor, etc.) are about $18.2M; the other capital charges (allowance for startup and modifications, interest during construction, etc.) make up the remaining $15.5M.

The capital investment for the limestone slurry process is $93.2M ($186.4/kW) in mid-1982 dollars. The total direct investment portion of the capital investment accounts for $45.7M. The major processing areas in this total direct investment are SO_2 absorption ($13.7M), particulate matter removal ($12.4M), and gas handling ($9.9M). These three areas account for about 79% of the direct investment. The indirect investments and the other capital charges account for $25.5M and $21.9M of the capital investment respectively.

The first-year and the levelized annual revenue requirements for the generic lime spray dryer process are $17.0M (6.20 mills/kWh) and $23.5M (8.55 mills/kWh) respectively. The major component of these revenue requirements is the levelized capital charges of $9.7M. Other important annual costs are maintenance ($1.9M), overheads ($1.8M), electricity ($1.5M), and lime ($1.0M).

The first-year and the levelized annual revenue requirements for the limestone slurry process are $23.5M (8.55 mills/kWh) and $32.2M (11.71 mills/kWh) respectively. Again, the major component of these revenue requirements is the levelized capital charges of $13.7M. Other major annual costs are maintenance ($3.5M), overheads ($3.0M), and electricity ($1.8M).

Comparisons

In terms of both capital investment and first-year annual revenue requirements, the base-case generic lime spray dryer process is substantially lower in cost than the base-case limestone slurry process as shown in Table S-2. The capital investment for the generic lime spray dryer process is about 29% lower, and the first-year annual revenue requirements are about 28% lower, than those for the limestone slurry process.

If these total capital investments are broken down into individual investment areas as shown in Table S-3, the reasons for the higher cost of the limestone slurry process are apparent. With the exception of the material handling area and particulate matter handling and recycle area (which the limestone slurry process does not have), the area investments for the limestone slurry process are higher than those for the generic lime spray dryer process. In fact the differences in only three areas, the SO_2 absorption, disposal area preparation, and gas-handling areas, account for a $12.8M difference in direct investment, or about $26.0M in total capital investment when the other capital charges are adjusted to reflect the higher direct investment.

TABLE S-3. SUMMARY OF THE TOTAL CAPITAL INVESTMENTS

Investment area	Total cost, k$	
	Generic lime spray dryer process	Limestone slurry process
Material handling	2,443	919
Feed preparation	599	1,071
Gas handling	7,190	9,924
SO_2 absorption	7,173	13,734
Particulate removal	11,133	12,395
Particulate handling and recycle	1,425	-
Solids disposal	379	1,453
Disposal area preparation	321	3,793
Land	515	910
All other capital costs	34,993	48,910
Total capital investment	66,171	93,109

Basis:
TVA design and economic premises.

The lower investment costs for the generic lime spray dryer process in these three areas are primarily due to the use of the spray dryer absorber. The design of the generic lime spray dryer process precludes the need for mist eliminators and the large recirculating slurry pumps which are used in the SO_2 absorption area of the limestone slurry process. The higher land and disposal area preparation costs (i.e., pond construction) for the limestone slurry process are due to the nature of the settled sludge in the pond (i.e., the sludge in the pond is only 40% solids) in contrast to the dry waste going to the landfill in the generic lime spray dryer process.

The first-year annual revenue requirements are broken down into various annual costs in Table S-4. Major cost differences between the processes are costs for raw materials, maintenance, and levelized capital charges. The higher raw material cost for the generic lime spray dryer process is due to the consumption of expensive lime ($102/ton) rather than limestone ($8.50/ton). Maintenance costs for the limestone slurry process are substantially higher because of the need to recirculate large amounts of limestone slurry through the process equipment. Levelized capital charges are higher for the limestone slurry process because of the higher total capital investment required.

TABLE S-4. SUMMARY OF FIRST-YEAR ANNUAL REVENUE REQUIREMENTS

	Total cost, $	
	Generic lime spray dryer process	Limestone slurry process
Raw materials	1,026,900	133,900
Operating labor and supervision	948,800	1,321,600
Electricity	1,485,600	1,764,300
Maintenance	1,939,400	3,464,700
Levelized capital charges	9,727,100	13,698,800
Other annual costs	1,912,600	3,120,500
Total first-year revenue requirements	17,040,400	23,503,800

SENSITIVITY ANALYSIS

Sensitivity to Raw Material Cost

The generic lime spray dryer process is more sensitive to changes in the delivered price of the raw material than the limestone slurry process. Because of the low-sulfur coal used and the low SO_2 removal requirement, however, cost changes from the base case do not significantly

change the economic results, as shown in Figure S-3. The generic lime spray dryer process has lower first-year annual revenue requirements regardless of the raw material prices selected.

The limestone slurry process, because of the low unit cost of limestone as well as the low-sulfur level in the coal and the low SO_2 removal requirement, is essentially insensitive to the delivered price of limestone.

Sensitivity to Raw Material Stoichiometry

Since the design stoichiometry for the limestone slurry process is based on the results from actual low-sulfur coal applications, only the base-case stoichiometry for the limestone slurry process was evaluated. The generic lime spray dryer process, however, represents technology which has not been demonstrated on a commercial scale and hence may change as this technology is developed further. Therefore, a range of raw material stoichiometries from 1.00 (-18.0%) to 1.46 (+19.7%) was evaluated.

The results of this sensitivity analysis are not significantly different from those previously discussed for the sensitivity to raw material prices (i.e., regardless of what reasonable raw material stoichiometry is used for the generic lime spray dryer process, the generic lime spray dryer process has a lower first-year annual revenue requirement than the base-case limestone slurry process) as shown in Figure S-4.

Sensitivity to Waste Disposal Costs

Since some power plant locations do not have sufficient land available for ponding of the limestone slurry process waste, the relative economics for a limestone slurry process with an alternative disposal method, the IUCS fixation process, were also evaluated. The limestone slurry process up to the point at which the purge stream leaves the scrubbers is identical for both cases. For the base-case limestone slurry process, the scrubbing waste is simply pumped to the pond and the supernate is returned to the process. For the limestone slurry - IUCS fixation process, the waste is pumped to a thickener and filter for dewatering, mixed with lime and fly ash, and allowed to set up before being hauled by truck to an onsite landfill for disposal.

The total capital investment for this combination limestone slurry - IUCS process is $91.4M ($183/kW) in 1982 dollars or nearly $2.0M less than the base-case limestone slurry process with ponding. This decrease in capital investment is due to the substantially lower disposal area preparation costs and land requirements for the IUCS alternative.

The first-year and the levelized annual revenue requirements for the limestone slurry - IUCS fixation process are $24.98M (9.08 mills/kWh) and $35.20M (12.80 mills/kWh) respectively. These costs are about 6% higher than those for the base case (i.e., with ponding) primarily because of the higher labor costs and related higher overhead costs.

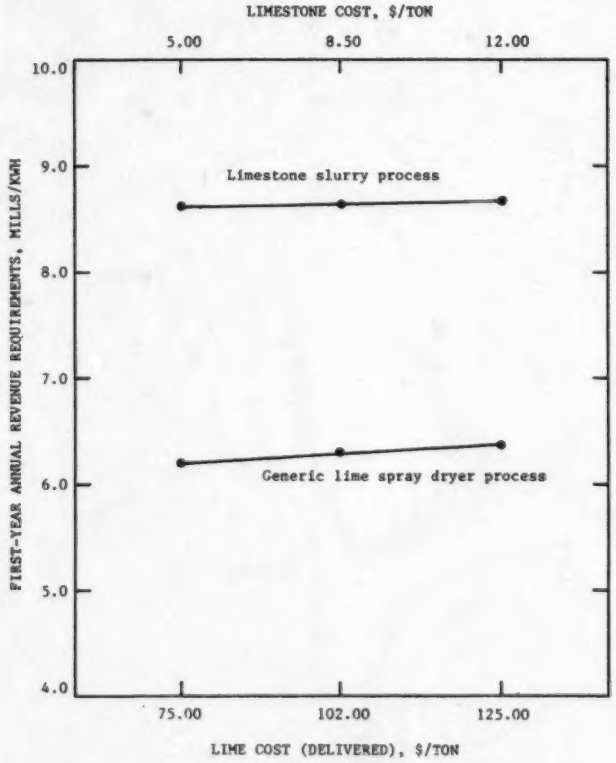

Figure S-3. Sensitivity of the first-year annual revenue requirements to the delivered cost of the raw material.

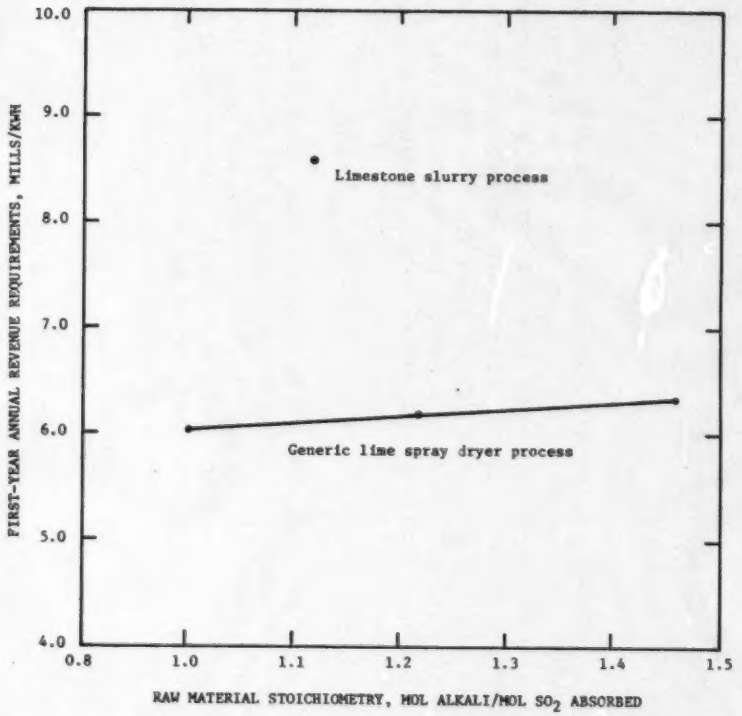

Figure S-4. Sensitivity of the first-year annual revenue requirements to the raw material stoichiometry in the absorber.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

For a new, 500-MW power unit burning a 0.7% sulfur subbituminous coal, the generic lime spray dryer process has a lower total capital investment and lower annual revenue requirements than a comparable limestone slurry process. These differences in capital investment and annual revenue requirements are larger than the uncertainty surrounding the comparability of preliminary economic estimates of this type (±10%). Therefore, for the assumed design and economic premises the generic lime spray dryer process appears to have a significant economic advantage over a conventional limestone slurry process.

For these design and economic premises, the generic lime spray dryer process maintains its economic advantage over the limestone slurry process for all ranges of raw material costs and raw material stoichiometries studied. The generic lime spray dryer process also has an economic advantage over a combined limestone slurry - IUCS process for fixation and landfill instead of ponding waste disposal.

Recommendations

Since only a single base-case application of the generic lime spray dryer process has been considered in this study, a definitive economic analysis of this process is suggested as the logical next step. Not only would the accuracy of the capital investment and annual revenue requirements for the base case be increased, but several case variations (power unit size, sulfur level in the coal, SO_2 removal efficiency, for example) could be evaluated.

Other areas which require additional study (and which will be evaluated in the final report for this project) include:

- Generic soda ash spray dryer process for a low-sulfur subbituminous coal application.
- Generic lime spray dryer process for a low-sulfur eastern coal application.
- Generic lime spray dryer process for a high-sulfur eastern coal application.

PRELIMINARY ECONOMIC ANALYSIS OF A LIME SPRAY DRYER FGD SYSTEM

INTRODUCTION

One of the recent developments in flue gas desulfurization (FGD), the so-called dry scrubbing technology using a concentrated solution or suspension (depending on whether the alkali material is sodium- or calcium-based) of a reactive absorbent in a spray dryer, is currently receiving a considerable amount of attention. Much of this interest is due to some potentially significant technical advantages over conventional wet FGD technology (primarily lime or limestone slurry scrubbing). In particular, the process design is relatively simple and a dry waste, rather than a wet sludge, is produced.

Nine contracts have been awarded for these dry scrubbers (listed in Table 1), six for commercial utility boilers and three for industrial boilers. With the exception of one utility boiler application which uses a sodium-based system, the systems under contract use lime-based spray dryer technology. Of the six utility boiler applications, three are lignite-fired boilers and three are fired with subbituminous coal. All six of these boiler fuels are relatively low in sulfur (<1%) and have a highly alkaline fly ash. Two of the three industrial boiler applications, on the other hand, involve eastern bituminous coals which have higher sulfur levels and relatively low alkalinity in the fly ash.

These dry scrubbers have one significant disadvantage--the use of an expensive (relative to limestone) alkali absorbent, either lime or soda ash. As long as the savings in capital charges and maintenance costs for the spray dryer systems are higher than the raw material cost penalty for lime or soda ash, the spray dryer systems will remain economically competitive with the wet limestone systems. This is one of the reasons that the first commercial applications are on utility boilers fired with lignite and subbituminous coals. Since both of these types of coals are normally low in sulfur, the amount of sulfur to be removed, and hence the consumption of expensive alkali raw material in the FGD system, is minimized. (In fact, the average sulfur levels in the fuels at the utility boilers currently under contract are all less than 1.0% sulfur.)

TABLE 1. CONTRACT AWARDS FOR SPRAY DRYER-BASED FGD SYSTEMS

Installation	Size, gross MW	Fuel type (% S)	SO_2 removal, %	Alkali raw material	Startup date	Vendor
Utility Boiler						
Coyote Unit 1	410	Lignite (0.78)	50	Soda ash	4/81	RI/WF[a]
Antelope Valley Unit 1	440	Lignite (0.68)	62	Lime	4/82	Joy/Niro[b]
Laramie River Unit 3	575	Subbituminous (0.54)	85	Lime	4/81	B&W[c]
Stanton Unit 2	63	Lignite (0.77)	73	Lime	9/82	R-C[d]
Springerville Unit 1	350	Subbituminous (0.69)	61	Lime	2/85	Joy/Niro
Springerville Unit 2	350	Subbituminous (0.69)	61	Lime	9/86	Joy/Niro
Rawhide Unit 1	250	Subbituminous (0.29)	70	Lime	12/83	Joy/Niro
Industrial Boiler						
Strathmore Paper Co.	14[e]	Bituminous (2.0-2.5)	75	Lime	7/79	Mikropul
Celanese	22[e]	Bituminous (1.0-2.0)	70-80	Lime	1/80	RI/WF
University of Minnesota	83[e]	Subbituminous (0.6-0.7)	70	Lime	9/81	Carborundum

a. Rockwell International/Wheelabrator-Frye.
b. Western Precipitation Division of Joy Manufacturing Company/Niro Atomizer, Inc.
c. Babcock and Wilcox.
d. Research-Cottrell.
e. Based on 2,900 aft^3/MW.

Another advantage for the spray dryer processes associated with these western coals is the relatively high alkalinity of the fly ash from these coals. Not only does this alkalinity react with sulfur in the boiler and thus reduce the amount of sulfur removal required in the FGD system, but the alkalinity in the fly ash also removes sulfur oxides (SO_x) from the flue gas in the spray dryer (if recycled) and thereby decreases the consumption of makeup alkali raw material.

Thus, in order to reflect the current utility market for these spray dryer systems, the fuel chosen for this study is a low-sulfur subbituminous coal containing a highly alkaline ash.

Although capital investments and revenue requirements for these dry scrubbing processes have been estimated by various process vendors and compared with a conventional wet limestone slurry process, no independent economic comparisons have been published. The purpose of this study is to make an economic comparison of a generic lime spray dryer process with a conventional wet limestone slurry process using the same design and economic premises.

In addition to these base-case evaluations, a sensitivity analysis is included in which the annual revenue requirements are calculated for various raw material costs and stoichiometries. The capital investment and annual revenue requirements for an alternate limestone slurry process with sludge fixation and landfill disposal are also included.

CONCLUSIONS

For a new, 500-MW power unit burning a 0.7% sulfur subbituminous coal, the generic lime spray dryer process has a lower total capital investment and lower annual revenue requirements than a comparable limestone slurry process. These differences in capital investment and annual revenue requirements are larger than the uncertainty surrounding the comparability of preliminary economic estimates of this type (±10%). Therefore, for the assumed design and economic premises the generic lime spray dryer process appears to have a significant economic advantage over a conventional limestone slurry process.

For these design and economic premises, the generic lime spray dryer process maintains its economic advantage over the limestone slurry process for all ranges of raw material costs and raw material stoichiometries studied. The generic lime spray dryer process also has an economic advantage over a combined limestone slurry - IUCS process for fixation and landfill instead of ponding waste disposal.

RECOMMENDATIONS

Since only a single base-case application of the generic lime spray dryer process has been considered in this study, a definitive economic analysis of this process is suggested as the logical next step. Not only would the accuracy of the capital investment and annual revenue requirements for the base case be increased, but several case variations (power unit size, sulfur level in the coal, SO_2 removal efficiency, for example) could be evaluated.

Other areas which require additional study (and which will be evaluated in the final report for this project) include:

- Generic soda ash spray dryer process for a low-sulfur subbituminous coal application.
- Generic lime spray dryer process for a low-sulfur eastern coal application.
- Generic lime spray dryer process for a high-sulfur eastern coal application.

DESIGN AND ECONOMIC PREMISES

This study compares the economics of two FGD systems on an equitable basis using conditions that are as representative as possible of projected industry conditions and that provide a clearly definable breakdown of costs into significant and useful divisions. The premises used in this study have been developed by the Tennessee Valley Authority (TVA), the U.S. Environmental Protection Agency (EPA), and others during similar economic evaluations made since 1967. Criteria of the premises are designed to establish efficiencies, process flow rates, and other operating and design conditions. The economic premises are designed to represent the many factors affecting costs.

DESIGN PREMISES

The utility plant design and operation is based on Federal Energy Regulatory Commission (FERC) historical data (1) and TVA experience. The conditions used are representative of a typical modern boiler for which FGD systems would most likely be considered. An Upper Great Plains and Rocky Mountain location typical of Wyoming, Colorado, Nebraska, and North and South Dakota is used because the concentration of both low-sulfur subbituminous coal supplies and power plants in this area make it representative of the segment of the power industry most attracted to the spray dryer FGD technology.

Although the FGD design is assumed to be proven, in keeping with current industry practice a redundant absorber train is provided to maintain acceptable boiler availability. In the integration of the absorber system with the boiler systems, provision for turndown and maintenance are limited to provision of a common plenum between the systems with dampers to allow individual trains to be shut down.

Emission Standards

New source performance standards (NSPS) established by EPA (2) specify a maximum emission, based on heat input, of 0.03 lb/MBtu for particulate matter, 1.2 lb/MBtu for SO_2, and 0.5 lb/MBtu for NO_x. In addition to meeting this maximum emission limit of 1.2 lb/MBtu for SO_2, the NSPS also require that new plants must reduce the uncontrolled SO_2 emissions from 70% to 90%, depending on the uncontrolled SO_2 emission level. For the low-sulfur subbituminous coal chosen in this study, this percentage SO_2 reduction is 70%. In addition it is assumed that the

boiler is designed to meet the 0.5 lb/MBtu NO_x standard and that the FGD system includes all the process equipment needed to meet both the 0.03 lb/MBtu particulate matter standard and the 70% SO_2 removal standard.

Fuel

The coal premises are composites of many samples representing major western coal production areas. The subbituminous coal is assumed to have a heating value of 9,700 Btu/lb and an ash content of 9.7% (both as fired) and a sulfur content of 0.7% (dry basis). The composition and flow rates for the base-case conditions are shown in Table 2. Although fly ash compositions are not normally of great significance in specifying a limestone FGD system, if the fly ash contains appreciable alkalinity it can have a significant effect on the economics of dry FGD systems which consume an expensive alkali raw material. Because of the high alkalinity of many western coals, a typical alkaline fly ash with the composition shown in Table 3 is used.

TABLE 2. COAL COMPOSITION AND FLOW RATE

Coal component	Wt % as fired	lb/hr
C	57.00	279,100
H	3.90	19,100
O	11.50	56,310
N	1.20	5,876
S	0.59	2,889
Cl	0.10	490
Ash	9.70	47,500
H_2O	16.00	78,350

Basis:
500-MW new coal-fired unit, 9,500 Btu/kWh, 9,700 Btu/lb heating value, 0.7% sulfur in coal, dry basis.

TABLE 3. FLY ASH ANALYSIS

Fly ash component	Wt %
SiO_2	32.2
Al_2O_3	17.4
Fe_2O_3	6.0
CaO	20.0
MgO	4.7
Na_2O	1.7
K_2O	0.5
TiO_2	1.0
SO_3	15.3
Other	1.2
Total	100.0

Power Plant Design

A single horizontal opposed, balanced-draft boiler for a 500-MW net electrical output is used. This net output does not include the power requirements for the FGD system. In contrast to some previous FGD studies by TVA, particulate matter removal and disposal have been included as part of the FGD unit rather than as part of the boiler because of the nature of the dry sorbent processes, which collect fly ash and sulfur salts simultaneously.

Power Plant Operation

An operating life of 30 years and a total operating lifetime of 130,500 hours are used. For this study a boiler capacity factor of 62.8% (equivalent to full load for 5,500 hr/yr) and a boiler heat rate of 9,500 Btu/kWh are used.

Flue Gas Composition

Flue gas compositions are the result of boiler design, fuel, and a variety of operating conditions. Combustion and emission conditions used to determine flue gas composition are based on balanced-draft boiler design and average values for the sulfur content of coal. Flue gas compositions are based on combustion of pulverized coal using a total air rate equivalent to 139% of the stoichiometric requirement. This includes 20% excess air to the boiler and 19% air inleakage in the boiler air heater. These values reflect TVA operating experience with horizontal, frontal-fired, coal-burning units. It is assumed that 80% of the ash present in coal is emitted as fly ash and 85% of the sulfur in coal is emitted as SO_x. Three percent of the SO_x emitted is assumed to be SO_3 and the remainder SO_2. The base-case flue gas composition and flow rates calculated for these conditions are shown in Table 4.

TABLE 4. BASE-CASE FLUE GAS COMPOSITION AND FLOW RATE

Flue gas component	Volume, %	lb/hr
N_2	73.09	3,887,000
O_2	5.39	327,200
CO_2	12.24	1,023,000
SO_2	0.04	4,760
SO_3	-	184
NO_x (as NO)	0.03	1,590
HCl	0.01	504
H_2O	9.20	314,600
Ash	-	38,000
Total	100.00	5,597,000

Basis:
500-MW new coal-fired unit, 9,500 Btu/lb heating value, 0.7% sulfur, dry basis, 1,754,000 aft^3/min at 300°F.

Absorber Design

Absorber design criteria are based on TVA operating experience, general power industry practice, and information from process and equipment vendors. The generic lime spray dryer process is based on vendor information. The limestone process is based on TVA experience at the Shawnee EPA Alkali Test Demonstration Facility, extensive power industry experience with these processes, and vendor information. Both the generic lime spray dryer and the limestone slurry processes are fed from a common plenum located downstream of the boiler air heaters. Both of these FGD processes consist of four parallel trains of absorbers of which three are operating and one is a spare. In addition, since only 70% SO_2 removal is required to meet the NSPS, part of the flue gas in both processes is bypassed around the absorbers for reheat purposes. The remaining flue gas passes through the absorbers where, depending on the process, the SO_2 removal is 80% to 90%. As the flue gas leaves the absorber, the hot bypassed flue gas is mixed with the scrubbed flue gas to obtain a 175°F recombined flue gas.

The generic lime spray dryer process feeds a single baghouse. Since the flue gas from these spray dryers is not saturated and does not contain entrained liquid, mist eliminators are not required. Induced-draft (ID) fans located between the baghouse and the stack are provided to compensate for the assumed total pressure drop of 12 inches H_2O for the generic lime spray dryer process.

The limestone slurry process is provided with high efficiency (99.8%) electrostatic precipitators (ESP) for particulate matter removal, venturi scrubber presaturators before the absorber, and chevron-type mist eliminators after the spray towers. The mist eliminators reduce the moisture content of the scrubbed gas to 0.1%. This reduces the reheating load, decreases deposition and corrosion in downstream equipment, and reduces particulate matter emission. A 16-inch H_2O pressure drop is assumed for the limestone slurry process, and in contrast to the generic lime spray dryer process which uses ID fans, a forced-draft (FD) fan is included between the boiler plenum and each venturi scrubber to compensate for this pressure drop. Operating conditions for the absorbers are shown in Table 5. These conditions are used for both the base-case and case variation studies. Cost scaling factors based on gas and product rates are used to calculate values at conditions other than the base case.

TABLE 5. DESIGN CONDITIONS FOR ABSORBER SYSTEM CALCULATIONS

Operating conditions	Generic lime spray dryer	Limestone
Presaturator		
Type	None	Venturi
Liquid		Scrubber liquid
Liquid/gas, gal/kaft^3		20
Pressure drop, in. H_2O		9
Absorber		
Type	Spray dryer	Spray tower
Slurry solids, %	22.5	15
Liquid/gas, gal/kaft^3	0.3	40
Pressure drop, in. H_2O	2	2
Liquid in exit gas, %	0.0	0.1
Slurry added, % solids	22.5	60
Effluent, % solids	100	15
Total pressure drop, in. H_2O	12	16

Reheat

Flue gas reheat to 175°F for both processes is provided by bypassing part of the incoming flue gas around the absorbers.

Raw Materials

The raw materials used for each process are listed below. Limestone is crushed and wet ground as part of the scrubbing operation. The lime is not processed before use.

Property	Limestone process	Generic lime spray dryer process
Size as received	0 - 1-3/4 in.	3/4 - 1-1/4 in.
Ground size	10% to pass 200 mesh	-
Analysis	90% $CaCO_3$	90% CaO
Bulk density, lb/ft^3	95	55

Waste Disposal

The disposal area is located one mile from the plant site. An earthen-diked, clay-lined pond, designed to minimize the sum of land and construction costs, is used for the limestone slurry process. Pond evaporation is assumed equal to rainfall. The limestone process waste is assumed to settle to a 40% solids sludge. An area-fill type landfill is used for the generic lime spray dryer process. The landfill size is based on a waste bulk density of 50 lb/ft^3 and a 30-ft fill depth.

Provisions for normal site maintenance of the pond and for normal landfill operations, including covering the waste and contouring to control runoff are included. No costs are provided for monitoring or post-operation maintenance.

ECONOMIC PREMISES

The economic premises are divided into capital costs for construction of the FGD system and annual revenue requirements for its operation. The premises are based on regulated utility economics using the design premises as a costing basis. The estimates use cost information obtained from engineering-contracting, processing, and equipment companies; raw material suppliers; and published cost indexes. Spray dryer costs were obtained by scaling vendor-supplied information. Raw material costs are based on those prevailing in the Upper Great Plains - Rocky Mountain region. Labor costs are assumed equivalent to those in the Midwest.

Capital Costs

The capital structure for the electric utility company is assumed to be:

Common stock	35%
Preferred stock	15%
Long-term debt	50%

The cost of capital is assumed to be:

Common stock	11.4%
Preferred stock	10.0%
Long-term debt	9.0%
Weighted cost of capital (based on capital costs above)	10.0%

The discount rate is 10%, the same as the weighted cost of capital.

For other economic factors needed in financial calculations, the following values are assumed:

Investment tax credit	10%
Federal and State income tax	50%
Property tax and insurance	2.5%
Annual inflation rate	6%

The levelized annual capital charge approach used in these premises is similar to that used by the Electric Power Research Institute (EPRI) (3).

Depreciation--

A 30-yr economic life and a 30-yr tax life are assumed for the utility plant. Salvage value is less than 10% and is equal to removal costs. The annual sinking fund factor for a 30-yr economic life and 10.0% weighted cost of capital is:

$$\text{Sinking fund factor} = \frac{WCC}{(1 + WCC)^n - 1} = 0.61\% \qquad (1)$$

where: n = economic life (in years)
WCC = weighted cost of capital (as a decimal fraction)

The use of the sinking fund factor does not indicate that regulated utilities commonly use sinking fund depreciation. The sinking fund factor is used since it is equivalent to straight-line depreciation levelized for the economic life of the facility using the weighted cost of capital.

An annual interim replacement allowance of 0.56% is also included as an adjustment to the depreciation account to ensure that the initial investment will be recovered within the actual rather than the forecasted life of the facility. Since power plant retirements occur at different ages, an average service life is estimated. Many different retirement dispersion patterns occur. The type S-1 Iowa State Retirement Dispersion pattern is used (4). This S-1 pattern is symmetrical with respect to the average-life axis and the retirements are represented to occur at a low rate over many years. The interim replacement allowance does not cover replacement of individual items of equipment since these are covered by the maintenance charge.

The sum of the years digits method of accelerated depreciation is used for tax purposes. On a levelized basis (using flow-through accounting) this results in a credit in the fixed charge rate as follows:

$$\text{Accelerated tax depreciation} = \frac{2CRF_B \left(n_T - \frac{1}{CRFT}\right)}{n_T \left(n_T + 1\right) (WCC)} \qquad (2)$$

where: CRF_B = Capital recovery factor (weighted cost of capital plus sinking fund factor) for the economic life (as a decimal fraction)

CRF_T = Capital recovery factor for the tax life (as a decimal fraction)

n_T = Tax life (in years)

$$\text{Levelized accelerated depreciation credit} = (ATD - SLD) \times \frac{ITR}{1 - ITR}$$

where: ATD = Accelerated tax depreciation (as a decimal fraction)
SLD = Straight-line depreciation (as a decimal fraction)
ITR = Income tax rate (as a decimal fraction)

For a 50% tax rate, 30-yr tax life, 30-yr book life, 10.0% weighted cost of capital, and 0.61% sinking fund factor, the annual levelized accelerated depreciation credit is 1.36% using flow-through accounting.

Investment Tax Credit--

The levelized investment tax credit is calculated as follows:

$$\text{Levelized investment tax credit} = \frac{(CRF_B)\ (\text{Investment tax credit rate})}{(1 + WCC)\ (1 - ITR)} \qquad (3)$$

where CRF_B, WCC, and ITR are the same factors previously defined in equations (1) and (2).

Using a 10.0% weighted cost of capital, 0.61% sinking fund factor, 10% investment tax credit rate, 50% income tax rate, the levelized investment tax credit is 1.92% annually.

Income Tax--

The levelized income tax is calculated as follows:

$$\text{Levelized income tax} = [CRF_B + AIR\text{-}SLD]\ \left[1 - \frac{\text{Debt Ratio} \times \text{Debt Cost}}{WCC}\right]\left[\frac{ITR}{1 - ITR}\right] \qquad (4)$$

where: AIR = Allowance for interim replacement

Using a 10.61% capital recovery factor (weighted cost of capital plus sinking fund factor), 0.56% allowance for interim replacements, 3.3% straight-line depreciation, 50% debt ratio, 9.0% debt cost, and a 50% income tax rate, the levelized income tax rate is 4.31%.

Annual Capital Charge--

The levelized annual capital charges for a publicly owned electric utility, as shown in Table 6, are 14.7% of the total investment. The annual capital charge includes charges for the capital recovery factor, interim replacements, insurance, and property taxes, State and Federal income taxes, and credits for investment credits and accelerated depreciation.

TABLE 6. LEVELIZED ANNUAL CAPITAL CHARGES FOR REGULATED UTILITY FINANCING

	Capital charge, %
Capital recovery factor	10.61
Interim replacements	0.56
Insurance and property taxes	2.50
Levelized income tax	4.31
Investment credit	(1.92)
Accelerated depreciation	(1.36)
Total	14.70

The annual capital charge is applied to the total capital investment. It is recognized that land and working capital (except spare parts) are not depreciable and that provisions must be made at the end of the economic life of the facility to recover their capital value. In addition, investment credit and accelerated depreciation credit cannot be taken for land and working capital (except spare parts). The cumulative effect of these factors makes an insignificant change in the annual capital charge rate and is therefore ignored.

Capital Investment Estimates

Capital investment estimates for this study are based on an Upper Great Plains and Rocky Mountain location and represent projects beginning in 1981 and ending in 1983. Capital cash flows for a standard project are assumed to be 25% the first year, 50% the second year, and 25% the third year of the project life. Capital costs for fixed assets are projected to mid-1982, which represents the approximate midpoint of the

construction expenditure schedule. The estimates in this study are based on a process description, flowsheet, material balance, and equipment list. These preliminary-level estimates are considered to have a -20% to +40% range of accuracy.

The total fixed capital investment consists of direct capital costs for equipment, building, utilities, service facilities, raw material and byproduct storage, waste disposal facilities, engineering design and supervision, construction expense, contractor fees, and contingency. The total capital investment consists of the total fixed capital investment plus allowances for startup and modifications, royalties, the cost of funds during construction, plus the cost of land and working capital.

Direct Capital Investment Process--

Direct capital costs cover process equipment, piping, insulation, transport lines, foundations, structures, electrical equipment, instrumentation, raw material and byproduct storage, site preparation and excavation, buildings, roads and railroads, trucks, and earthmoving equipment. Direct investment costs are prepared using the average annual Chemical Engineering (5) cost indexes and projections as shown in Table 7.

TABLE 7. COST INDEXES AND PROJECTIONS

Year	1978	1979[a]	1980[a]	1981[a]	1982[a]	1983[a]	1984[a]
Plant	218.8	240.2	259.4	278.9	299.8	322.3	344.9
Material[b]	240.6	262.5	286.1	309.0	333.7	360.4	385.6
Labor[c]	185.9	209.7	226.5	244.6	264.2	285.3	305.3

a. TVA projections.
b. Same as index in Chemical Engineering (5) for "Equipment, machinery, supports."
c. Same as index in Chemical Engineering (5) for "Construction labor."

The overtime premium for 7% overtime is included in the construction labor. Appropriate amounts for sales tax and for freight are included in the process capital costs.

Direct Capital Investment - Utilities, Services and Miscellaneous--

Necessary electrical substations and conduit and steam, process water, fire and service water, instrument air, chilled water, inert gas, and compressed air distribution facilities are included in the utilities investment. These facilities are costed as increments to the facilities already required by the power plant. Service facilities such as maintenance

shops, stores, communications, security, offices, and road and railroad facilities are estimated on the basis of process requirements. Services, non-power plant utilities, and miscellaneous costs will normally be in the range of 4% to 8% of the total process capital depending on the type of process. A 6% rate is used in this evaluation for both processes.

Indirect Capital Investment--

Indirect capital investment covers engineering design and supervision, architect and engineering contractor costs, construction costs, contractor fees, and contingency. Construction facilities (which include costs for mobile equipment, temporary lighting, construction roads, raw water supply, construction safety and sanitary facilities) and other similar expenses incurred during construction are considered as part of construction expenses and are charged to indirect capital investment.

Listed below are the indirect costs used:

	% of direct investment
Engineering design and supervision	7
Architect and engineering contractor	2
Construction expense	16
Contractor fees	5
Total	30

A contingency of 20% is included because projects normally have a higher likelihood of exceeding rather than underrunning the capital estimate. While actual projects could properly have both project and process contingencies of varying amounts, depending on the type and developmental maturity of the process, comparability among processes could be skewed by the use of different contingencies in the same study.

Other Capital Charges--

Startup and modification allowances are estimated at 8% to 12% of the total fixed investment depending upon the complexities of the process being studied. For these processes a midpoint value of 10% of the total fixed investment was assumed.

Cost of funds during construction is 15.6% of the total fixed investment for each process. This factor is equivalent to the 10% weighted cost of capital with 25% of the construction expenditures of the first year, 50% the second year, and 25% the third year of the project construction schedule. Expenditures are assumed uniform over each year. Startup costs are assumed to occur late enough in the project schedule that there are no charges for the use of money used to pay startup costs.

For both processes, royalty fees of 0.5% of the direct investment are charged. Land cost is assumed to be $5,000 per acre.

Working capital is the total amount of money invested in raw materials, supplies, finished and semifinished products, accounts receivable, and monies on deposit for payment of operating expenses such as salaries, wages, raw materials, purchases, taxes, and accounts payable. For these premises, working capital is defined as the equivalent cost of 1 month's raw material, 1.5 months' conversion cost, and 1.5 months' plant and administrative overhead costs. In addition, it includes an amount equal to 3% of the total direct investment to cover spare parts, accounts receivable, and monies on deposit to pay taxes and accounts payable.

Annual Revenue Requirements

Annual revenue requirements use 1984 costs and are based on 5,500 hours of operation per year at full load. Annual revenue requirements are divided into direct costs and indirect costs. Both first-year and levelized annual revenue requirements are determined. Levelized annual revenue requirements are based on a 10% discount factor and a 6% inflation rate over the 30-yr life of the power unit. Direct costs consist of raw materials, labor, utilities, maintenance, and analytical costs. Indirect costs consist of levelized annual capital charges and overheads.

Direct Costs--

Projected raw material, labor, and utility costs are listed in Table 8. Unit costs for steam and electricity are based on the assumption that the required energy is purchased from another source. Unit costs ($/kW, mills/kWh) are calculated on the basis of net power output of the boiler excluding the electricity consumed by the pollution control systems. Actually, electrical use by the pollution control equipment after the ESP will result in a derating of the utility plant for either a new or a retrofitted unit. To minimize iterative calculations, the pollution control equipment is charged with purchased electricity instead of derating the utility plant.

Maintenance costs are estimated as a percentage of the direct investment, based on unit size and process complexity. For the limestone slurry process, non-pond maintenance is 8% and pond maintenance is 3%. For the generic lime spray dryer process, maintenance is 6%.

Indirect Costs--

The levelized annual capital charges consist of a sinking fund factor, an allowance for interim replacement, property taxes, insurance, weighted cost of capital, income tax, credits for accelerated depreciation, and investment credit. The levelized annual capital charge for a regulated utility, as was shown in Table 6, is 14.7%.

TABLE 8. PROJECTED 1984 UNIT COSTS FOR RAW MATERIALS, LABOR, AND UTILITIES

	$/unit
Raw materials	
Limestone	8.50/ton
Lime	102.00/ton
Labor	
Operating labor	15.00/man-hr
Analyses	21.00/man-hr
Mobile equipment	21.00/man-hr
Utilities	
Process water[a]	0.14/kgal
Electricity	0.037/kWh

a. Varies according to process-dependent water requirements.

Plant and administrative overhead is 60% of conversion costs less utilities. The plant and administrative overheads include plant services such as safety, cafeteria, medical, plant protection, janitor, purchasing personnel, general engineering (excluding maintenance), interplant communications and transportation, recreational facilities, and the expenses connected with management activities. Fringe benefits such as retirement, vacation, dental and medical plans are included in the base wage rates.

PROCESS BACKGROUND AND DESCRIPTION

GENERIC LIME SPRAY DRYER PROCESS

The generic lime spray dryer process (Figure 1 and Table 9) is a relatively simple processing system requiring few items of process equipment. Makeup lime is slurried, atomized into the flue gas stream, and the resulting waste material is collected along with the fly ash in the baghouse. The concentration of the lime slurry is adjusted so that the amount of water injected into the flue gas stream does not saturate the flue gas. Mist eliminators (a frequent source of operating problems) are not required. In addition, since the flue gas stream is unsaturated, the waste material is collected as dry particulate matter.

In this particular application (primarily due to both the relatively low SO_2 removal required and the highly alkaline nature of the fly ash), most of the collected waste material is reslurried and recycled through the spray dryer. This recycling of waste material increases the lime utilization in the process and thereby reduces the consumption of this costly alkali raw material. The waste that is not recycled is trucked to a landfill for disposal.

Flue gas bypass around the spray dryer is used in this application because it is more economical to treat part of the flue gas at a higher SO_2 removal efficiency than to remove 70% of the SO_2 from all of the flue gas. By using flue gas bypass and having hot ($\approx 300^{\circ}F$) flue gas available for reheat, the spray dryer can be operated so that the treated flue gas more closely approaches the flue gas saturation temperature. As the flue gas approaches saturation temperature, the alkali droplets retain their moisture longer and increase the liquid-phase residence time for SO_2 absorption. This results in a better raw material utilization (as well as a higher SO_2 removal efficiency) in the spray dryer. Although there is an additional capital investment for the flue gas bypass ductwork, this is offset by both the lower capital investment for the spray dryers and the lower annual cost for lime.

Process Description

Flue gas from the boiler air heater enters the three operating trains (the fourth is a spare) of the FGD system through a common plenum. Most of the flue gas (78%) from the plenum passes directly into the top of the spray dryers. The rest of the flue gas bypasses the spray dryers for reheat purposes. The spray dryer contains an atomizing system

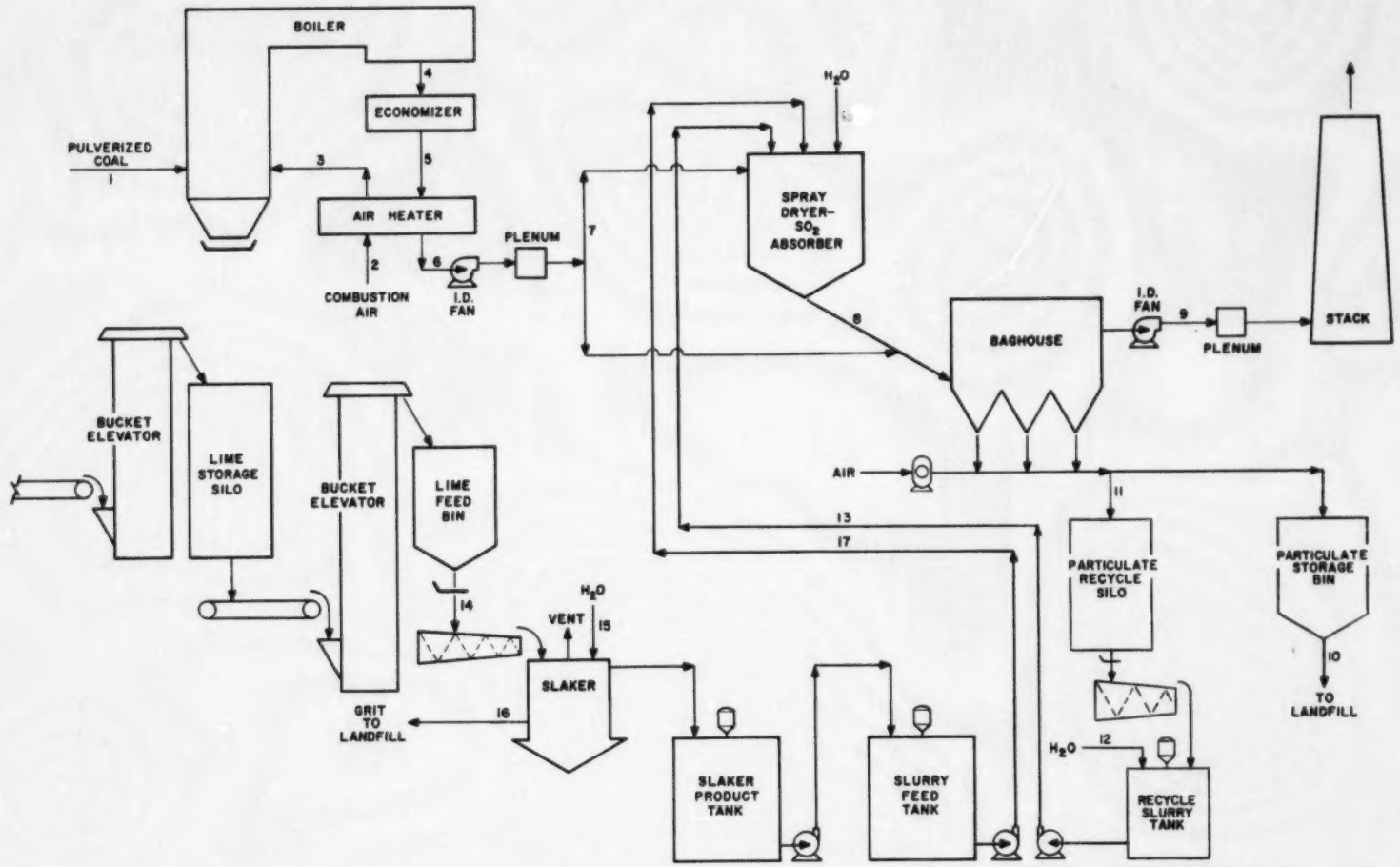

Figure 1. Generic lime spray dryer process. Flow diagram.

TABLE 9. GENERIC LIME SPRAY DRYER PROCESS

MATERIAL BALANCE

	Stream No.	1	2	3	4	5
	Description	Coal to boiler	Combustion air to air heater	Combustion air to boiler	Gas to economizer	Gas to air heater
1	Total stream, lb/hr	489,700	5,119,000	4,419,000	4,897,000	4,897,000
2	sft^3/min at 60°F		1,131,000	976,400	1,045,000	1,045,000
3	Temperature, °F		80	535	890	705
4	Pressure, psig					
5	gpm					
6	Specific gravity					
7	pH					
8	Undissolved solids, %					
9						
10						

	Stream No.	6	7	8	9	10
	Description	Gas to FGD system	Gas to spray dryer	Gas from spray dryer	Gas to stack[a]	Waste to landfill
1	Total stream, lb/hr	5,597,000	4,547,000	4,743,000	5,715,000	44,650
2	sft^3/min at 60°F	1,200,000	975,000	1,020,000	1,250,000	
3	Temperature, °F	300	300	160	175	
4	Pressure, psig					
5	gpm					
6	Specific gravity					
7	pH					
8	Undissolved solids, %					
9						
10						

	Stream No.	11	12	13	14	15
	Description	Waste to recycle particulate silo	Makeup water to recycle slurry tank	Recycle slurry to spray dryer	Makeup lime to slaker	Makeup water to slaker
1	Total stream, lb/hr	55,450	83,150	138,600	3,661	11,350
2	sft^3/min at 60°F					
3	Temperature, °F					
4	Pressure, psig					
5	gpm		166			23
6	Specific gravity					
7	pH					
8	Undissolved solids, %			40		
9						
10						

	Stream No.	16	17	18		
	Description	Grit to landfill	Lime slurry to spray dryer	Dilution water to spray dryer		
1	Total stream, lb/hr	366	14,650	19,890		
2	sft^3/min at 60°F					
3	Temperature, °F			60		
4	Pressure, psig					
5	gpm			40		
6	Specific gravity					
7	pH					
8	Undissolved solids, %		22.5			
9						
10						

a. Includes air inleakage into the baghouse.

designed to spray the lime slurry and a waste recycle slurry perpendicularly to the gas flow in the spray dryer. (The lime slurry and the waste recycle slurry are combined into a single stream and atomized in the spray dryer.) The SO_x and HCl in the flue gas react readily with the lime slurry by the following reactions:

$$Ca(OH)_2 + SO_2 \rightarrow CaSO_3 + H_2O\uparrow \quad (5)$$

$$Ca(OH)_2 + SO_3 \rightarrow CaSO_4 + H_2O\uparrow \quad (6)$$

$$Ca(OH)_2 + 2HCl \rightarrow CaCl_2 + 2H_2O\uparrow \quad (7)$$

In addition to these primary reactions, the following secondary reaction also occurs:

$$CaSO_3 + 1/2O_2 \rightarrow CaSO_4 \quad (8)$$

The water content of the feedstreams is controlled so that all of the water fed to the spray dryer evaporates and the mixed calcium salts and fly ash leave the spray dryer as dry particulate matter entrained in the flue gas. Since the flue gas is not saturated and contains no liquid carryover, mist eliminators are not required. The particulate matter-laden flue gas from the bottom of the spray dryer is mixed with the 300°F flue gas which bypassed the spray dryer and is passed to the baghouse. The baghouse not only removes the fly ash and the calcium-based particulate matter from the flue gas, but it also significantly increases the contact time between the calcium-based particulate matter and the SO_2-containing flue gas. This increased contact time leads to the additional conversion of both SO_x by reactions (5) and (6) and $CaSO_3$ by reaction (8). The flue gas from the baghouse passes through an ID fan and is vented to the stack. The flue gas enters the stack at about 175°F and, therefore, additional reheat is not required.

The fabric bags in the baghouse are cleaned periodically. The particulate matter drops into hoppers at the bottom of the baghouse. Pneumatic conveyors move the particulate matter to either the recycle storage silos or the waste storage bins. Waste solids from the silo are reslurried with makeup water and recycled through the spray dryer. The waste storage bin is emptied into trucks for transport to a landfill.

Bulk shipments of pebble lime are received by rail and sent to the storage silo. The lime is periodically moved to intermediate storage bins from which process requirements are removed. The pebble lime from the bins is slaked with makeup water and pumped as a 22.5% slurry to the lime slurry tank. This makeup slurry is pumped to the spray dryer as needed.

Analysis of Processing Subsections

To facilitate cost determinations and comparisons, the lime process is divided into seven processing sections and the processing equipment is assigned to the appropriate section. The equipment list, giving the description and cost of each equipment item by section, is shown in Table 10. These costs do not include the investment required for foundations, structures, electrical components, piping, instruments and controls, etc. Each of these processing sections is described in more detail below.

Material Handling--

This and the following section, feed preparation, compose the raw material receiving and preparation section. The material handling section includes all of the equipment to receive lime by rail and to maintain a supply of lime to the weigh feeders. It includes a lime storage silo with a 30-day capacity and two lime feed bins each having a 12-hr capacity.

Feed Preparation--

The feed preparation sections include the equipment necessary to convert the makeup lime into slurry for SO_2 absorption. Two trains of lime preparation equipment (feeders, slakers, tanks, and agitators) are used. Each train is sized to handle 50% of the full load capacity. A slurry feed tank with a 4-hr capacity is provided.

Gas Handling--

Included in this area is an inlet plenum interconnecting the flue gas ducts which feed the scrubber trains. It also includes the bypass ducting around the spray dryers. Four ID fans are provided between the baghouse and the stack to compensate for the pressure drop through the FGD system.

SO_2 Absorption--

Four spray dryers are provided (three operating and one spare); each is sized to handle one-third of the total flue gas volume.

Particulate Removal--

A single baghouse containing 28 compartments and the associated equipment is provided.

Particulate Handling and Recycle--

A single train of equipment to store, reslurry, and recycle the waste material is provided. Two particulate storage bins are included to provide a 24-hr capacity for waste material to be landfilled.

Waste Disposal--

This section contains no processing equipment. It includes trucks to transport the waste absorbent to the landfill and earthmoving equipment

TABLE 10. GENERIC LIME SPRAY DRYER PROCESS

BASE-CASE EQUIPMENT LIST, DESCRIPTION, AND COST

Area 1--Material Handling

Item	No.	Description	Total material cost, 1982 $	Total labor cost, 1982 $
1. Conveyor, lime unloading (enclosed)	1	Belt, 24 in. x 1,500 ft long, 30 hp, 100 tons/hr, 200 ft/min	390,000	242,800
2. Elevator, storage silo	1	Continuous bucket, 16 in. x 8 in. x 11-3/4 in., 75 ft lift, 15 hp, 100 tons/hr, 160 ft/min	33,600	3,300
3. Silo, lime storage	1	40 ft dia x 50 ft straight side, 62,800 ft^3, 60° slope, carbon steel	65,200	194,300
Vibrators	1	Bin activator, 10 ft dia	14,000	1,300
4. Conveyor, live lime feed	1	Belt, 14 in. x 100 ft long, 2 hp, 16 tons/hr, 100 ft/min	23,800	7,600
5. Elevator, live lime feed	2	Continuous bucket, 8 in. x 5-1/2 in. x 7-3/4 in., 35 ft lift, 2 hp, 16 tons/hr, 150 ft/min	49,300	4,000
6. Bin, lime feed	2	11 ft dia x 12 ft straight side, 1,140 ft^3, 60° slope, w/cover, carbon steel	10,600	28,200
7. Dust collecting system	1	Bag filter, polypropylene bag, 2,200 ft^3/min, 7-1/2 hp (1/2 cost in feed preparation area)	3,900	600
Subtotal			590,400	482,100

(continued)

TABLE 10 (continued)

Area 2--Feed Preparation

	Item	No.	Description	Total material cost, 1982 $	Total labor cost, 1982 $
1.	Feeder, lime bin discharge	2	Vibrating, 3-1/2 hp, carbon steel	8,400	800
2.	Feeder, slaker	2	Screw, 12 in. dia x 12 ft long, 1 hp, 2 tons/hr	6,600	400
3.	Slaker	2	5 hp slaker, 1 hp classifier, 1.0 ton/hr	72,500	23,900
4.	Tank, slaker product	2	6 ft dia x 8 ft high, 1,700 gal, open top, four 6 in. baffles, agitator supports, carbon steel, neoprene lined	5,400	7,500
5.	Agitator, slaker product tank	2	2 turbines, 24 in. dia, 3 hp, neoprene coated	15,800	1,800
6.	Pump, slaker product tank	3	Centrifugal, 40 gpm, 50 ft head, 1-1/2 hp, carbon steel, neoprene lined (2 operating, 1 spare)	5,300	2,300
7.	Tank, slurry feed	1	10 ft dia x 12 ft high, 7,100 gal, open top, four 10 in. baffles, agitator supports, carbon steel, neoprene lined	6,500	9,500
8.	Agitator, slurry feed tank	1	40 in. dia, 7-1/2 hp, neoprene coated	15,300	1,300
9.	Pump, slurry feed tank	8	Centrifugal, 40 gpm, 200 ft head, 5 hp, carbon steel, neoprene lined (3 operating, 5 spare)	40,000	6,000
10.	Dust collecting system	1	Bag filter, polypropylene bag, 2,200 ft^3/min, 7-1/2 hp, (1/2 cost in material handling area)	3,900	600
	Subtotal			179,700	54,100

(continued)

TABLE 10 (continued)

Area 3--Gas Handling

Item	No.	Description	Total material cost, 1982 $	Total labor cost, 1982 $
1. Fan	4	Induced draft, 382,000 aft^3/min, 12 in. static head, 875 rpm, 1,250 hp, fluid drive, double width, double inlet (4 operating)	1,583,600	99,600
Subtotal			1,583,600	99,600

Area 4--SO_2 Absorption

Item	No.	Description	Total material cost, 1982 $	Total labor cost, 1982 $
1. Spray dryer	4	48 ft dia x 54 ft high, with 3 rotary atomizers, carbon steel, (3 operating, 1 spare)	4,324,000	548,000
Subtotal			4,324,000	548,000

Area 5--Particulate Removal

Item	No.	Description	Total material cost, 1982 $	Total labor cost, 1982 $
1. Baghouse	1	Automatic fabric filter, 28 compartments, 2.5 air-to-cloth ratio	8,262,000	2,871,100
Subtotal			8,262,000	2,871,100

(continued)

TABLE 10 (continued)

Area 6--Particulate Handling and Recycle

	Item	No.	Description	Total material cost, 1982 $	Total labor cost, 1982 $
1.	Conveyor, particulate feed to bin	1	Pneumatic, pressure-vacuum, 250 hp	243,100	75,600
2.	Bin, particulate storage	2	24 ft dia x 25 ft straight side, 11,300 ft^3, 60° slope, w/cover, carbon steel	43,600	131,400
	Vibrator	2	Bin activator, 10 ft dia	18,600	2,500
3.	Silo, particulate recycle	2	25 ft dia x 30 ft straight side, 14,700 ft^3, 60° slope, w/cover, carbon steel	51,200	149,700
4.	Feeder, particulate	2	Vibrating, 3-1/2 hp, carbon steel	8,400	800
5.	Feeder, recycle slurry tank	2	Screw, 12 in. dia x 12 ft long, 5 hp, 50 tons/hr	30,800	4,500
6.	Tank, recycle slurry	1	21 ft dia x 23 ft high, 55,400 gal, open top, four 21 in. baffles, agitator supports, carbon steel, neoprene lined	25,700	38,700
7.	Agitator, recycle slurry tank	1	84 in. dia, 30 hp, neoprene coated	42,100	2,600
8.	Pump, recycle slurry feed	8	Centrifugal, 80 gpm, 200 ft head, 10 hp, carbon steel, neoprene lined (3 operating, 5 spare)	65,400	7,600
	Subtotal			528,900	413,400

Basis: Most equipment cost estimates are based on informal vendor quotes and TVA information. The only exception is the cost for the spray dryers which is based on information supplied by the vendor.

These costs represent equipment costs only. Costs for piping, electrical equipment, instruments, foundations, and other installation costs are not included. The differences in area costs between the equipment list and the capital summary sheets are due to these installation costs.

to distribute the waste evenly throughout the landfill. Therefore, these costs are not shown in the equipment list, but rather they are listed as a direct investment component of the capital investment.

LIMESTONE SLURRY PROCESS

The limestone slurry process (Figure 2 and Table 11) is also a relatively simple processing system requiring few items of process equipment. Although not usually considered as part of the FGD system, a high-efficiency (99.8%) ESP has been included in the limestone slurry process upstream of the FGD system. This change in the typical economic analysis of the limestone slurry process (i.e., including the cost of the ESP's) is necessary to provide comparability with the generic lime spray dryer process.

Another significant design change for the limestone slurry process is the inclusion of partial flue gas bypass around the scrubber. Since only 70% SO_2 removal is required in this low-sulfur coal application, it was considered more economical to design the FGD system for 90% SO_2 removal and treat only enough flue gas to meet the required SO_2 reduction. Under these conditions sufficient heat is available from the bypassed gas to eliminate the need for additional reheat.

Otherwise the limestone slurry process is of conventional design. The makeup limestone is ground, slurried, and added as needed to maintain a 15% solids slurry recirculating through the scrubber. A purge stream is bled off the absorber loop and is pumped to the disposal pond. The pond supernate is recycled and reused in the process. The fly ash from the ESP is trucked to and disposed of in the pond.

Process Description

The flue gas from the boiler air heater passes through both the high-efficiency ESP and the power plant ID fans before entering a common plenum. This common plenum distributes the gas to four trains of FD booster fans and absorbers. (Three of these scrubber trains are operating and one is a spare.) These FD booster fans are provided downstream of the plenum to compensate for the pressure drop in the FGD system.

Approximately 28% of the 300°F flue gas from the booster fan bypasses the venturi/spray tower absorbers and enters the ducts downstream from the absorbers for reheat purposes. The remaining flue gas enters a venturi absorber where the flue gas, in contact with recirculated limestone slurry, is adiabatically cooled and saturated. This cooled flue gas enters the spray tower absorbers and passes countercurrently to the recirculating 15% solids limestone slurry which absorbs the SO_x. The absorbers are equipped with chevron-type mist eliminators. Absorber outlet gas is heated from 130°F to 175°F before entering the stack by mixing with the bypassed flue gas.

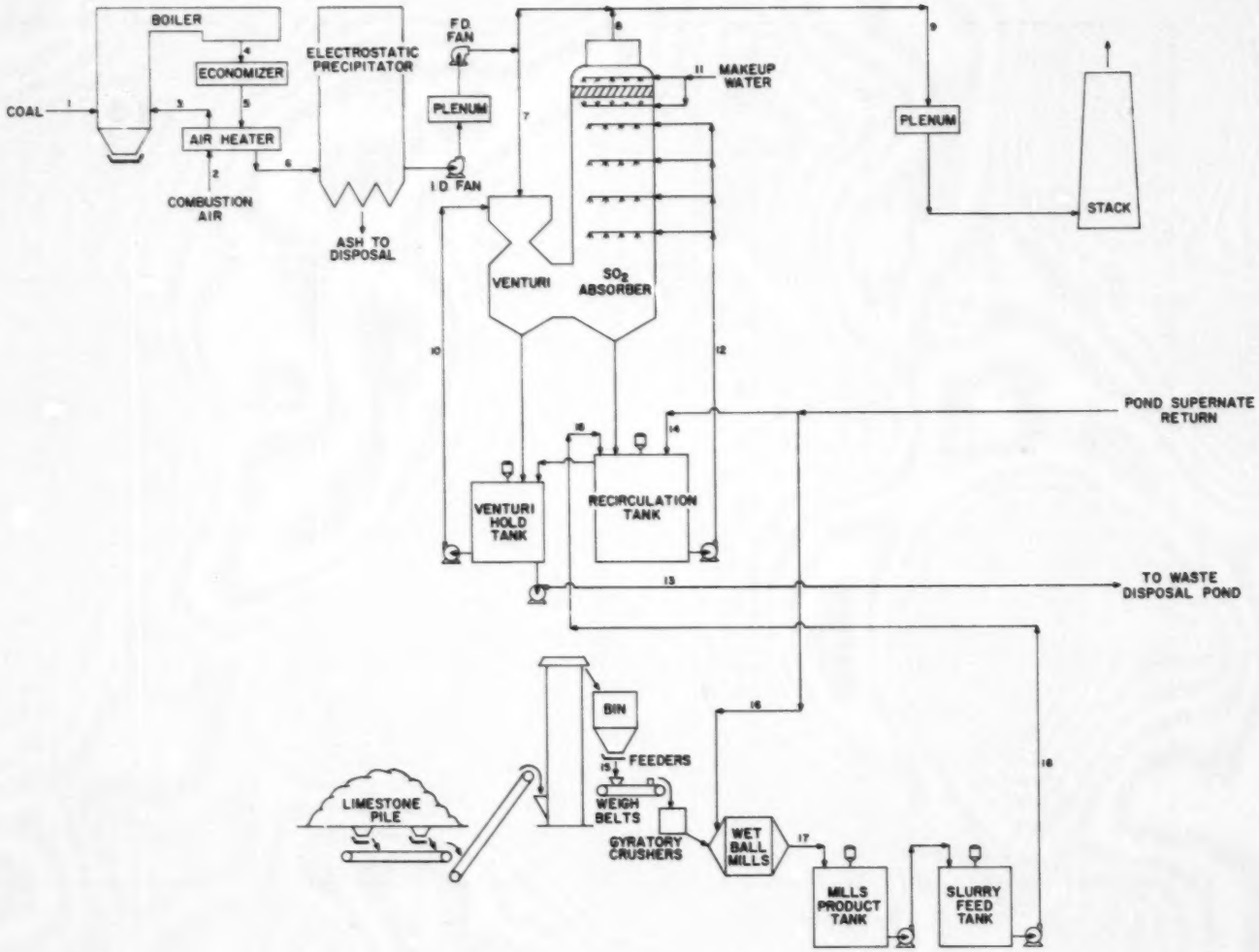

Figure 2. Limestone slurry process. Flow diagram.

TABLE 11. LIMESTONE SLURRY PROCESS

MATERIAL BALANCE

	Stream No.	1	2	3	4	5
	Description	Coal to boiler	Combustion air to air heater	Combustion air to boiler	Gas to economizer	Gas to air heater
1	Total stream, lb/hr	489,700	5,119,000	4,419,000	4,897,000	4,897,000
2	aft^3/min at 600F		1,131,000	976,400	1,045,000	1,045,000
3	Temperature, °F		80	535	890	705
4	Pressure, psig					
5	gpm					
6	Specific gravity					
7	pH					
8	Undissolved solids, %					
9						
10						

	Stream No.	6	7	8	9	10
	Description	Gas to ESP	Gas to venturi	Gas from absorber	Gas to stack	Recycle slurry to venturi
1	Total stream, lb/hr	5,597,000	4,002,000	4,170,000	5,727,000	11,520,000
2	aft^3/min at 600F	1,200,000	863,200	922,300	1,259,000	
3	Temperature, °F	300	300	130	175	
4	Pressure, psig					
5	gpm					20,930
6	Specific gravity					
7	pH					
8	Undissolved solids, %					15
9						
10						

	Stream No.	11	12	13	14	15
	Description	Makeup water to scrubber	Recirculated slurry to absorber	Slurry to pond	Pond supernate to recirculation tank	Limestone to weigh belts
1	Total stream, lb/hr	170,100	23,050,000	48,810	26,690	5,728
2	aft^3/min at 600F					
3	Temperature, °F		130			
4	Pressure, psig					
5	gpm	340	41,860	89	53	
6	Specific gravity					
7	pH					
8	Undissolved solids, %		15	15		
9						
10						

	Stream No.	16	17	18		
	Description	Pond supernate to wet ball mill	Mills product tank feed	Makeup slurry to recirculation tank		
1	Total stream, lb/hr	3,820	9,546	9,546		
2	aft^3/min at 600F					
3	Temperature, °F					
4	Pressure, psig					
5	gpm	8	12	12		
6	Specific gravity					
7	pH					
8	Undissolved solids, %		60	60		
9						
10						

A bleedstream from the recirculation tank is fed to the pond feed tank from which it is pumped to the onsite pond. The solids in the slurry settle to form a sludge containing approximately 40% solids. The pond supernate is recycled to the wet ball mills and the absorber recirculation tank.

Makeup limestone is received by rail and stored in a pile onsite. The limestone is removed from the pile and fed first to gyratory crushers and then to ball mills where it is wet ground to 70% minus 200 mesh. The effluent from the ball mill is stored as a 60% solids slurry, first in the ball mill product tank and then in the slurry feed tank. This makeup limestone slurry is pumped to the absorber recirculation tank where it is combined with scrubber effluent slurry and recycle pond water to maintain a 15% solids content in the recirculating slurry.

Analysis of Processing Subsections

To facilitate cost determinations and comparisons, the limestone slurry process is divided into six processing sections and the processing equipment is assigned to the appropriate section. The equipment list, giving the description and cost of each equipment item by section, is shown in Table 12. These costs do not include the investment required for foundations, structures, electrical components, piping, instruments, and controls, etc. Each of these processing sections is described below.

Material Handling--

This area includes all of the facilities needed for receiving the raw limestone, areas for a storage stockpile sufficient for 30 days at normal operating conditions, and an in-process limestone storage for 24 hours.

Feed Preparation--

A single train of gyratory crushers and wet ball mills to convert the raw limestone to a 70% minus 200 mesh, 60% solids slurry is included in this area. It also contains a product storage tank with capacity equal to an 8-hr supply of makeup slurry.

Particulate Removal--

Four high-efficiency ESP units (99.8% removal) are included in this area. These ESP's are sized for a low-sulfur, western coal application.

Gas Handling--

Included in this area is one inlet flue gas plenum interconnecting the four flue gas ducts which feed the absorbers and four FD fans. Also included are the FD fans and the bypass ducting around the absorbers. Each of these FD fans is sized to handle one-third of the total flue gas volume and to compensate for the pressure drop in the FGD system.

TABLE 12. LIMESTONE SLURRY PROCESS

BASE-CASE EQUIPMENT LIST, DESCRIPTION, AND COST

Area 1--Materials Handling

Item	No.	Description	Total material cost, 1982 $	Total labor cost, 1982 $
1. Mobile equipment	1	Bucket tractor	60,800	-
2. Hopper, reclaim	1	7 ft x 4-1/4 ft x 2 ft deep, carbon steel	700	1,300
3. Feeder, live limestone storage	1	Vibrating pan, 3.5 hp	15,400	2,700
4. Pump, tunnel sump	2	Vertical, 60 gpm, 70 ft head, 5 hp, carbon steel, neoprene lined (1 operating, 1 spare)	4,300	1,100
5. Conveyor, live limestone feed	1	Belt, 30 in. wide x 100 ft long, 2 hp, 100 tons/hr, 60 ft/min	34,300	6,300
6. Conveyor, live limestone feed (incline)	1	Belt, 30 in. wide x 190 ft long, 40 hp, 35 ft lift, 100 tons/hr, 60 ft/min	48,000	20,300
7. Elevator, live limestone feed	1	Continuous bucket, 12 in. x 8 in. x 11-3/4 in., 75 hp, 90 ft lift, 100 tons/hr, 160 ft/min	102,800	2,400
8. Bin, crusher feed	1	13 ft dia x 21 ft high, w/ cover, carbon steel	6,900	14,500
9. Dust collecting system	1	Bag filter, polypropylene bag, 2,200 aft^3/min, 7-1/2 hp, automatic shaker system	6,700	18,100
Subtotal			279,900	66,700

(continued)

TABLE 12 (continued)

Area 2--Feed Preparation

	Item	No.	Description	Total material cost, 1982 $	Total labor cost, 1982 $
1.	Feeder, crusher	1	Weigh belt, 18 in. wide x 14 ft long, 2 hp, 3.0 tons/hr	23,100	1,800
2.	Crusher	1	Gyratory, 0 x 1-1/2 to 3/4 in., 75 hp, 3.0 tons/hr	67,700	7,600
3.	Ball mill	1	Wet, open system, 100 hp, 3.0 tons/hr	174,400	17,800
4.	Tank, mills product	1	10 ft dia x 10 ft high, 5,500 gal, open top, four 10 in. baffles, agitator supports, carbon steel, flakeglass lined	6,200	11,000
5.	Agitator, mills product tank	1	36 in. dia, 10 hp, neoprene coated	10,500	500
6.	Pump, mills product tank	2	Centrifugal, 12 gpm, 60 ft head, 1 hp, carbon steel, neoprene lined (1 operating, 1 spare)	6,200	1,400
7.	Tank, slurry feed	1	11 ft dia x 11 ft high, 7,500 gal, open top, four 11 in. baffles, agitator supports, carbon steel, flakeglass lined	4,300	10,500
8.	Agitator, slurry feed tank	1	44 in. dia, 15 hp, neoprene coated	11,000	900
9.	Pump, slurry feed tank	6	Centrifugal, 4 gpm, 60 ft head, 1/4 hp, carbon steel, neoprene lined (3 operating, 3 spare)	17,700	4,300
10.	Dust collecting system	1	Bag filter, polypropylene bag, 2,200 aft^3/min, 7-1/2 hp, automatic shaker system	6,700	18,100
	Subtotal			328,200	73,900

(continued)

TABLE 12 (continued)

Area 3--Particulate Removal

Item	No.	Description	Total material cost, 1982 $	Total labor cost, 1982 $
1. ESP	4	99.8% removal efficiency SCA = 700	8,020,000	4,010,000
2. Conveyor, flyash to particulate bin	1	Pneumatic, pressure-vacuum, 75 hp	109,800	69,300
3. Bin, particulate	2	25 ft dia x 27 ft high, w/cover, carbon steel	39,000	108,600
4. Vibrator	2	Bin activator, 10 ft dia	28,000	2,600
Subtotal			8,196,800	4,190,500

Area 4--Gas Handling

Item	No.	Description	Total material cost, 1982 $	Total labor cost, 1982 $
1. Fans	4	Forced draft, 421,000 aft^3/min, 16 in. static head, 890 rpm, 2,250 hp, fluid drive, double width, double inlet (3 operating, 1 spare)	2,276,200	147,500
Subtotal			2,276,200	147,500

Area 5--SO_2 Absorption

Item	No.	Description	Total material cost, 1982 $	Total cost, labor 1982 $
1. Venturi absorber	4	L/G = 20, pressure drop = 9 in. H_2O (3 operating, 1 spare)	632,900	86,000

(continued)

TABLE 12 (continued)

Area 5 (continued)

Item	No.	Description	Total material cost, 1982 $	Total labor cost, 1982 $
2. Tank, venturi hold	4	15-1/2 ft dia x 31-1/2 ft high, 44,500 gal, open top, four 15-1/2 in. wide baffles, agitator supports, carbon steel, flakeglass lined (3 operating, 1 spare)	63,700	156,300
3. Agitator, venturi hold tank	4	62 in. dia, 40 hp, neoprene coated (3 operating, 1 spare)	96,900	32,700
4. Pumps, venturi recycle	8	Centrifugal, 7,000 gpm, 100 ft head, 350 hp, carbon steel, neoprene lined (3 operating, 5 spare)	421,000	37,000
5. SO_2 absorber	4	Spray tower, 34 ft long x 17 ft wide x 40 ft high, 1/4 in. carbon steel, neoprene lining; FRP spray headers, 316 stainless steel chevron vane entrainment separator and nozzles (3 operating, 1 spare)	3,485,000	401,200
6. Tank, recirculation	4	31-1/2 ft dia x 31-1/2 ft high, 184,200 gal, open top, four 31-1/2 in. wide baffles, agitator supports, carbon steel, flakeglass lined (3 operating, 1 spare)	158,400	354,500
7. Agitator, recirculation tank	4	124 in. dia, 60 hp, neoprene coated (3 operating, 1 spare)	293,300	99,100
8. Pump, slurry recirculation	12	Centrifugal, 7,000 gpm, 100 ft head, 350 hp, carbon steel, neoprene lined (6 operating, 6 spare)	631,500	55,600

(continued)

TABLE 12 (continued)

Area 5 (continued)

	Item	No.	Description	Total material cost, 1982 $	Total labor cost, 1982 $
9.	Pump, makeup water	2	Centrifugal, 2,620 gpm, 200 ft head, 250 hp, carbon steel (1 operating, 1 spare)	25,600	2,700
10.	Soot blowers	44	Air, retractable	377,100	318,700
	Subtotal			6,185,400	1,543,800

Area 6--Solids Disposal

	Item	No.	Description	Total material cost, 1982 $	Total labor cost, 1982 $
1.	Tank, pond feed	1	15-1/2 ft dia x 31-1/2 ft high, 44,500 gal, open top, agitator supports, four 15-1/2 in. baffles, carbon steel, flake-glass lined	15,900	39,100
2.	Agitator, pond feed tank	1	2 turbines, 52 in. dia, 40 hp, neoprene coated	21,700	1,800
3.	Pumps, pond feed	4	Centrifugal, 89 gpm, 130 ft head, 3 hp, carbon steel, neoprene lined (2 operating, 2 spare)	18,200	3,900
4.	Pumps, pond return	2	Centrifugal, 127 gpm, 200 ft head, 10 hp, carbon steel, neoprene lined (1 operating, 1 spare)	6,200	700
	Subtotal			62,000	45,500

Basis: Most equipment cost estimates are based on informal vendor quotes and TVA information.

These costs represent equipment costs only. Costs for piping, electrical equipment, instruments, foundations, and other installation costs are not included. The differences in area costs between the equipment list and the capital summary sheets are due to these installation costs.

SO_2 Absorption--

Four trains (three operating, one spare) of venturi/spray tower absorbers with mist eliminators, recirculation tanks, and recirculating pumps are included. Each absorber train is sized to handle one-third of the total flue gas volume.

Solids Disposal--

Included are one pond feed tank with agitator, pond feed and pond return pumps, and mobile equipment (trucks) to move the fly ash from the ESP to the sludge pond.

ECONOMIC EVALUATION AND COMPARISON

Based on the power plant, process design, economic premises, and the specific process equipment for each process described in the previous sections, preliminary capital investment, first-year revenue requirements, and levelized annual revenue requirements were prepared for the economic evaluation and comparison of the generic lime spray dryer process and a conventional limestone slurry process.

Both first-year and levelized annual revenue requirements are calculated. First-year annual revenue requirements are useful for comparing the relative cost differences between processes for their first year of operation, and they are an indicator of the magnitude of the annual revenue requirements. However, these first-year annual revenue requirements do not represent the actual cost of operating the plant since they do not consider either the time-value of money or the inflationary pressures over the life of the plant. In order to reflect these costs, a levelizing factor (1.886) is applied to the first-year annual revenue requirements to give a levelized annual revenue requirement. This levelizing factor is based on a 10% discount factor and a 6% inflation rate over the 30-yr life of the power unit.

Sensitivity analyses have also been performed to evaluate the effects of varying the raw material price and stoichiometry for the generic lime spray dryer process. An alternate case involving sludge fixation for the limestone slurry process has also been included.

Even though the generic lime spray dryer process, as described and costed, was assumed to be proven technology, the current status of development does not fully justify this assumption since none of the lime spray dryer processes have been operated on a commercial, coal-fired boiler. However, for TVA cost estimation purposes each system is assumed to be proven technology.

ACCURACY OF ESTIMATES

The accuracy associated with these preliminary cost estimates, i.e., -20%, +40%, is defined as the relationship between the estimated costs and what the actual installed costs for the process might be. The accuracy assigned to a cost estimate is empirical and not related to variabilities in a statistical sense, but rather, it depends on both the amount and the quality of the technical data available. Accuracy ranges reflect the numerous uncertainties surrounding estimates made using simplifying assumptions. For example, in a preliminary-level estimate

in which only a flowsheet, material balance, and an equipment list are available--and all other indirect investments are factored--the uncertainty surrounding the investment is much greater than a definitive-level estimate where quantities and costs for piping, electrical equipment, instruments, etc., are calculated rather than factored. Therefore when estimating the preliminary-level capital investment for a particular process for a particular installation the uncertainty surrounding the costs would be -20%, +40%.

However, when comparing the preliminary-level costs for two competing process technologies, many of the same simplifying assumptions are made for each of the processes and therefore the comparability is much greater than the accuracy of the estimates. When directly comparing two similar level estimates, the uncertainty ranges associated with the compared costs are estimated at only $\pm$10%.

CAPITAL INVESTMENT

Generic Lime Spray Dryer Process

The total capital investment for the generic lime spray dryer process is $66.2M ($132/kW) in mid-1982 dollars. This total cost can be broken down into the various investment cost categories as shown in Table 13. The total direct investment, which includes processing equipment, piping, etc., accounts for about 49% of the total capital investment. The indirect investments such as engineering design and supervision, architect and engineering contractor, construction expense, contractor fees, and project contingency make up about 28% of the total capital investment. The various other capital charges (allowance for startup and modifications, interest during construction, royalties, land, and working capital) make up the remaining 23%.

The total direct investment for the generic lime spray dryer process can be further subdivided into the various processing areas. The major investment areas are the particulate matter removal, gas handling, and SO_2 absorption areas. These areas account for most (78%) of the total direct investment.

Major indirect investments are project contingency at $8.4M and the construction expense at $5.2M. Engineering design and supervision, contractor fees, and architect and engineering contractor expense contribute significantly less at $2.3M, $1.6M, and $0.7M respectively.

Other capital charges, including allowance for startup and modifications, interest during construction, royalties, land, and working capital, account for $15.5M of the total capital investment. The allowance for startup and modifications and interest during construction contributed most to the other capital charges. Land and royalties were relatively insignificant at $0.5M and $0.2M.

TABLE 13. GENERIC LIME SPRAY DRYER PROCESS

TOTAL CAPITAL INVESTMENT

(500-MW new coal-fired power unit, 0.7% S in coal; 70% SO_2 removal; onsite solids disposal)

	Investment, k$
Direct Investment	
Material handling	2,443
Feed preparation	599
Gas handling	7,190
SO_2 absorption	7,173
Particulate removal	11,133
Particulate handling and recycle	1,425
Solids disposal	379
Total process capital	30,342
Services, utilities, and miscellaneous	1,821
Total direct investment excluding disposal field preparation	32,163
Disposal field preparation	321
Total direct investment	32,484
Indirect Investment	
Engineering design and supervision	2,274
Architect and engineering contractor	650
Construction expense	5,197
Contractor fees	1,624
Contingency	8,446
Total fixed investment	50,675
Other Capital Charges	
Allowance for startup and modifications	5,068
Interest during construction	7,905
Royalties	162
Land	515
Working capital	1,846
Total capital investment	66,171
Dollars of total capital per kW of generation capacity	132.3

Basis

Upper Midwest plant location represents project beginning mid-1980, ending mid-1983. Average cost basis for scaling, mid-1982.

Minimum in-process storage, redundant scrubber train, and pumps are spared.

Disposal area located one mile from power plant.

FGD process investment begins at boiler air heater exit. Boiler plenum and stack excluded.

Only nominal construction overtime included.

Limestone Slurry Process

The total capital investment for the base-case application of the limestone slurry process (a combined particulate-limestone FGD system) is $93.2M ($186/kW) in mid-1982 dollars, as shown in Table 14.

The direct investment for the limestone slurry process can be further subdivided into the various processing areas. SO_2 absorption, particulate matter removal, and gas handling account for nearly 79% of the total direct investment. The waste disposal pond construction represents about 8% of the total direct investment.

The major indirect investments are project contingency ($11.9M), construction expense ($7.3M), contractor fees ($2.3M), and engineering design and supervision ($3.2M). Architect and engineering contractor costs are significantly less ($0.9M).

The remaining $22.0M of the total capital investment is other capital charges. The allowance for startup and modifications and interest during construction together contribute nearly 20% of the total capital investment and make up 83% of the other capital charges. Royalties, land, and working capital are $0.2M, $0.9M, and $2.6M respectively.

Comparison

The total direct investment and the total capital investment for the two FGD systems are shown in Table 15. The generic lime spray dryer process is substantially (29%) less capital intensive than a limestone slurry process.

TABLE 15. BASE-CASE TOTAL DIRECT INVESTMENTS AND TOTAL CAPITAL INVESTMENTS

Process	Total direct investment		Total capital investment	
	M$	$/kW	M$	$/kW
Generic lime spray dryer	32.5	65.0	66.3	132.6
Limestone slurry	45.7	91.3	93.2	186.4

The major investment differences between the generic lime spray dryer process and the limestone slurry process are in the SO_2 absorption, particulate matter removal, solids disposal equipment, and the waste disposal area preparation as shown in Table 16. With the exception of the investment for the material handling and feed preparation areas, the limestone slurry costs are higher than the costs for the corresponding areas in the generic lime spray dryer process. The lower costs for the generic lime spray dryer process in the other areas are due primarily to the use of the spray dryer. The spray dryer technology eliminates the

TABLE 14. LIMESTONE SLURRY PROCESS

TOTAL CAPITAL INVESTMENT

(500-MW new coal-fired power unit, 0.7% S in coal; 70% SO_2 removal; onsite solids disposal)

	Investment, k$
Direct Investment	
Material handling	919
Feed preparation	1,071
Particulate removal	12,395
Gas handling	9,924
SO_2 absorption	13,734
Solids disposal	1,453
Total process capital	39,496
Services, utilities, and miscellaneous	2,370
Total direct investment excluding pond construction	41,866
Pond construction	3,793
Total direct investment	45,659
Indirect Investment	
Engineering design and supervision	3,196
Architect and engineering contractor	913
Construction expense	7,305
Contractor fees	2,283
Contingency	11,871
Total fixed investment	71,227
Other Capital Charges	
Allowance for startup and modifications	7,123
Interest during construction	11,111
Royalties	228
Land	910
Working capital	2,590
Total capital investment	93,189
Dollars of total capital per kW of generation capacity	186.38

Basis
- Upper Midwest plant location represents project beginning mid-1980, ending mid-1983. Average cost basis for scaling, mid-1982.
- Minimum in-process storage, redundant scrubber train, pumps are spared.
- Disposal pond located one mile from power plant.
- FGD process investment begins at boiler air heater exit. Boiler plenum and stack excluded.
- Only nominal construction overtime included.

need for slurry recirculating tanks and pumps and mist eliminators in the SO_2 absorption area and the thickeners and filtration equipment in the solids disposal area. The higher land and disposal area preparation costs for the limestone process are due to both the type of disposal (pond versus landfill) and the nature of the settled sludge in the pond (i.e., the sludge in the pond is only 40% solids as compared to a dry product going to the landfill in the generic lime spray dryer process).

TABLE 16. SUMMARY OF THE TOTAL CAPITAL INVESTMENTS

Investment area	Total cost, k$	
	Generic lime spray dryer process	Limestone slurry process
Material handling	2,443	919
Feed preparation	599	1,071
Gas handling	7,190	9,924
SO_2 absorption	7,173	13,734
Particulate removal	11,133	12,395
Particulate handling and recycle	1,425	-
Solids disposal	379	1,453
Disposal area preparation	321	3,793
Land	515	910
All other capital costs	34,993	48,910
Total capital investment	66,171	93,189

Basis:
TVA design and economic premises.

ANNUAL REVENUE REQUIREMENTS

Generic Lime Spray Dryer Process

The first-year annual revenue requirements for the generic lime spray dryer process as applied to the previously described base case are $17.04M in 1984 dollars as shown in Table 17. This corresponds to a first-year unit revenue requirement of 6.20 mills/kWh. Equivalent levelized annual revenue requirements for the generic lime spray dryer process are $23.52M, or 8.55 mills/kWh.

Annual direct costs (including raw material and conversion costs) are $5.52M or slightly more than 32% of the total first-year annual revenue requirements. Indirect costs, primarily capital charges but also including overhead costs, account for the remaining 68%.

The major direct costs are maintenance ($1.9M), electricity ($1.5M), and lime ($1.0M). Together these three items account for 26% of the first-year annual revenue requirements. The other major annual costs are the levelized capital charges of $9.7M and overheads of $1.8M or 57.1% and 10.5% of the total first-year annual revenue requirements respectively.

TABLE 17. GENERIC LIME SPRAY DRYER PROCESS

ANNUAL REVENUE REQUIREMENTS

(500-MW new coal-fired power unit, 0.7% S in coal;
70% SO_2 removal; onsite solids disposal)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs - First-Year			
Raw materials			
Lime	10,068 tons	102.00/ton	1,026,900
Total raw materials cost			1,026,900
Conversion costs			
Operating labor and supervision			
FGD	25,400 man-hr	15.00/man-hr	381,000
Solids disposal	27,040 man-hr	21.00/man-hr	567,800
Utilities			
Process water	74,440 kgal	0.14/kgal	10,400
Electricity	40,151,000 kWh	0.037/kWh	1,485,600
Maintenance			
Labor and material			1,939,400
Analyses	4,160 man-hr	21.00/man-hr	87,400
Waste disposal operation	122,500 tons	0.15/ton	18,400
Total conversion costs			4,490,000
Total direct costs			5,516,900
Indirect Costs - First-Year			
Overheads			
Plant and administrative (60% of conversion costs less utilities)			1,796,400
Total first-year operating and maintenance costs			7,313,300
Levelized capital charges (14.7% of total capital investment)			9,727,100
Total first-year annual revenue requirements			17,040,400
Levelized first-year operating and maintenance costs (1.886 first-year O and M)			13,792,900
Levelized annual revenue requirements			23,520,000

	M$	Mills/kWh
First-year annual revenue requirements	17.04	6.20
Levelized annual revenue requirements	23.52	8.55

Basis
Upper Midwest plant location, 1984 revenue requirements.
Remaining life of power plant, 30 years.
Power unit on-stream time, 5,500 hr/yr.
Coal burned, 1,347,000 tons/yr, 9,500 Btu/kWh.
Total direct investment, $32,484,000; total fixed investment, $50,675,000; and total capital investment, $66,171,000.

Limestone Slurry Process

The first-year annual revenue requirements for the limestone slurry process are $23.50 as shown in Table 18. This corresponds to a first-year unit revenue requirement of 8.55 mills/kWh. Equivalent levelized annual revenue requirements are $32.19M or 11.71 mills/kWh.

Annual direct costs for raw materials, labor, utilities, and maintenance are $6.8M, or only 29% of the first-year revenue requirements. Indirect costs, primarily for capital charges but also including overhead costs, account for the remaining 71%.

Raw material costs for the limestone slurry process are about $0.1M. The conversion costs are nearly $5.9M, with the major costs being maintenance and electricity at $3.5M and $1.8M respectively. As would be expected, the levelized capital charge at $13.7M was the major annual expense, representing 58% of the total first-year annual revenue requirements.

Comparison

The first-year and the levelized annual revenue requirements for each of the FGD processes are shown in Table 19. The generic lime spray dryer process is approximately 27% lower in cost (6.20 mills/kWh versus 8.55 mills/kWh) than the limestone slurry process in terms of both first-year costs and levelized annual revenue requirements.

TABLE 19. BASE-CASE TOTAL FIRST-YEAR AND LEVELIZED ANNUAL REVENUE REQUIREMENTS

Process	Total first-year revenue requirements		Levelized annual revenue requirements	
	M$	Mills/kWh	M$	Mills/kWh
Generic lime spray dryer	17.04	6.20	23.52	8.55
Limestone slurry	23.50	8.55	32.19	11.71

Table 20 compares the various component costs of the first-year revenue requirements for each process. The major cost difference between the processes is the cost for capital charges, maintenance, raw materials, and overheads (primarily because of the differences in maintenance costs). The $0.7M difference in raw material costs between the limestone slurry process and generic lime spray dryer process (limestone is much cheaper than lime) is essentially cancelled by the higher capital charges of the limestone slurry process. Utility costs (electricity and process water) are about the same for both processes although electrical costs are slightly higher for the limestone slurry process.

TABLE 18. LIMESTONE SLURRY PROCESS

ANNUAL REVENUE REQUIREMENTS

(500-MW new coal-fired power unit, 0.7% S in coal; 70% SO_2 removal; onsite solids disposal)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs - First-Year			
Raw materials			
Limestone	15,800 tons	8.50/ton	133,900
Total raw materials cost			133,900
Conversion costs			
Operating labor and supervision			
FGD	61,900 man-hr	15.00/man-hr	928,500
Solids disposal	18,720 man-hr	21.00/man-hr	393,100
Utilities			
Process water	99,670 kgal	0.14/kgal	14,000
Electricity	47,683,000 kWh	0.037/kWh	1,764,300
Maintenance			
Labor and material			3,464,700
Analyses	6,240 man-hr	21.00/man-hr	131,000
Waste disposal operation	104,500 tons	0.15/ton	15,700
Total conversion costs			6,711,300
Total direct costs			6,845,200
Indirect Costs - First-Year			
Overheads			
Plant and administrative (60% of conversion costs less utilities)			2,959,800
Total first-year operating and maintenance costs			9,805,000
Levelized capital charges (14.7% of total capital investment)			13,698,800
Total first-year annual revenue requirements			23,503,800
Levelized first-year operating and maintenance costs (1.886 first-year O and M)			18,492,200
Levelized annual revenue requirements			32,191,000

	M$	Mills/kWh
First-year annual revenue requirements	23.50	8.55
Levelized annual revenue requirements	32.19	11.71

Basis

Upper Midwest plant location, 1984 revenue requirements.
Remaining life of power plant, 30 years.
Power unit on-stream time, 5,500 hr/yr.
Coal burned, 1,347,000 tons/yr, 9,500 Btu/kWh.
Total direct investment, $45,659,000; total fixed investment, $71,227,000; and total capital investment, $93,189,000.

TABLE 20. SUMMARY OF THE TOTAL FIRST-YEAR REVENUE REQUIREMENTS

	Total cost, $	
	Generic lime spray dryer process	Limestone slurry process
Raw materials	1,026,900	133,900
Operating labor and supervision	948,800	1,321,600
Electricity	1,485,600	1,764,300
Maintenance	1,939,400	3,464,700
Levelized capital charges	9,727,100	13,698,800
Overheads	1,796,400	2,959,800
Other annual costs	116,200	160,700
Total first-year revenue requirements	17,040,400	23,503,800

The higher maintenance charge for the limestone process is due to both the larger number of equipment items needed and the problems associated with handling and recirculating a corrosive and erosive scrubbing slurry.

SENSITIVITY ANALYSIS

Sensitivity to Raw Material Prices

The sensitivity of the first-year annual revenue requirements for the generic lime spray dryer process and the limestone slurry process to the delivered raw material cost was calculated. The results of this sensitivity analysis are shown in Figure 3.

Although the generic lime spray dryer process is more sensitive than the limestone slurry process to changes in the delivered price of the raw material, the low-sulfur nature of the coal and the low SO_2 removal requirement preclude changes from the base-case costs from significantly changing the economic results. The generic lime spray dryer process has lower first-year annual revenue requirements regardless of the raw material prices selected. For example, a 25% increase (or decrease) in the delivered cost of lime results in only a 1.3% increase (or decrease) in the first-year annual revenue requirements for the generic lime spray dryer process. This is still 26.5% less than the first-year annual revenue requirements for the base-case limestone slurry process.

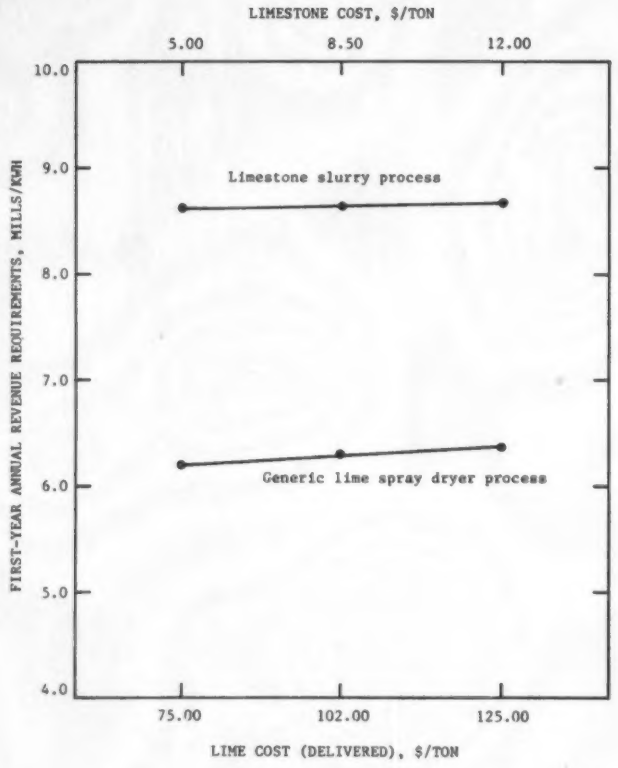

Figure 3. Sensitivity of the first-year annual revenue requirements to the delivered cost of the raw material.

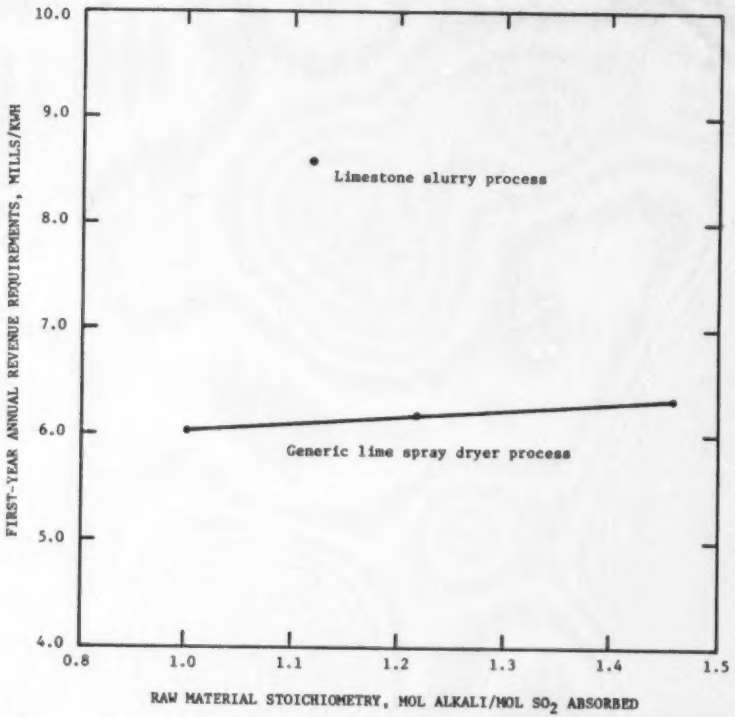

Figure 4. Sensitivity of the first-year annual revenue requirements to the raw material stoichiometry in the absorber.

The limestone slurry process, due to the low unit cost of limestone as well as the lower sulfur level in the coal and the lower SO_2 removal requirements, is essentially insensitive to the delivered price of limestone.

Sensitivity to Raw Material Stoichiometry

Since the generic lime spray dryer process technology has only been demonstrated on a pilot-plant scale, the assumed stoichiometry in the spray dryer could change as the technology is developed further. In addition, the alkalinity in the fly ash from low-sulfur coals may vary between coals. The required lime stoichiometry for coals with the same sulfur content could change, depending on the fly ash alkalinity of coal being burned. Therefore, a sensitivity analysis showing the changes in total first-year revenue requirements as the raw material stoichiometry in the spray dryer is changed has been included.

Table 21 lists both the base-case and the alternative stoichiometries used in the sensitivity analysis. The raw material stoichiometries given are in mols of alkali per mol of SO_2 absorbed. The range of stoichiometries shown for the generic lime spray dryer process is 1.00 (-18.0%) to 1.46 (+19.7%).

The capital investments for each processing area are adjusted by using area scale factors and the ratio of raw material flow rates through each area. Processing areas that are sized independently of the raw material rates (gas handling and SO_2 absorption) are the same for each of the alternative stoichiometries. Many of the processing areas that are dependent on the raw material flow rate contribute only minor amounts to the capital investment. For example, a 19.7% increase in raw material flow rate increases the capital investment only about 2%.

The annual revenue requirements for the generic lime spray dryer process are somewhat more sensitive to the raw material stoichiometry than the raw material cost. For example, a 19.7% increase in the raw material stoichiometry results in a 3.1% increase in first-year revenue requirements. However, from these results (as shown in Figure 4) it is apparent that stoichiometry changes over a wide range will have little effect on the capital investment and annual revenue requirement relationships of the two processes.

Sensitivity to Waste Disposal Costs

An alternate limestone slurry process in which the waste sludge is dewatered and fixed before disposal in a landfill is included for comparison purposes. For this alternate process, the front end of the limestone slurry process (through the venturi/spray tower absorbers) is identical to the base-case limestone slurry process. The major difference is that the absorber slurry bleed is treated using a process similar to the IU Conversion Systems, Inc. (IUCS) fixation process. In this process

TABLE 21. COMPARISON OF TOTAL CAPITAL INVESTMENT AND FIRST-YEAR UNIT REVENUE REQUIREMENTS FOR THE GENERIC LIME SPRAY DRYER PROCESS AT VARIOUS RAW MATERIAL STOICHIOMETRIES

Process	Raw material stoichiometry			Total capital investment		First-year unit revenue requirements	
	Variation	Value[a]	% change[b]	$/kW	% change[b]	Mills/kWh	% change[b]
Generic lime spray dryer	Low	1.00	-18.0	129.9	-1.8	6.02	-2.9
	Base	1.22	-	132.3	-	6.20	-
	High	1.46	19.7	135.0	2.0	6.39	3.1
Limestone slurry	Base	1.12	-	186.4	-	8.55	-

a. Raw material stoichiometry is defined as mols of alkali per mol of SO_2 absorbed.
b. Change is calculated relative to the base-case value.

the mixed sulfite-sulfate sludge, rather than being pumped to a pond for disposal, is dewatered, using a thickener and a filter, to 60% solids, mixed with dry fly ash and lime, and trucked to an onsite landfill for disposal.

The capital investment for this process was estimated from the base-case limestone slurry process capital investment by deleting the disposal area preparation (pond construction) and sludge transportation charges and including the investment required for the IUCS process equipment and the landfill preparation. The total capital investment for the limestone slurry-IUCS process is $91.4M (vs. $93.2M for the base-case limestone slurry process). The lower capital investment for the limestone slurry-IUCS process is the result of the much lower landfill preparation costs ($0.23M for the landfill vs. $3.79M for the pond), which overcome the costs ($2.66M) for the additional equipment (thickeners and filters).

The first-year and the levelized annual revenue requirements for the limestone slurry-IUCS process are $24.98M (9.08 mills/kWh) and $35.20M (12.80 mills/kWh) respectively. These costs are about 6% higher than those for the base case (i.e., with ponding). Although the levelized capital charges are lower ($0.2M) for the limestone slurry-IUCS process, this savings is completely offset by the higher labor costs ($0.88M) and the higher overheads ($0.62M).

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